Surface Soil Structure
On Reclaimed Well Sites
FINAL REPORT

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ABSTRACT

A variety of physical properties were measured on eight Alberta wellsite leases and corresponding off-lease soils over a period of three years. The lease sites were chosen to represent wellsite reclamation conditions in Alberta prior to 1983, a period when topsoil removal and replacement was not required. The study was designed to find out whether leases reclaimed without topsoil reformed surface soil structure similar to that of the surrounding soils.

Pedological investigations done in the first year of the study demonstrated easily recognizable differences in macromorphological properties between lease and control soils. However, thrice-replicated, field measurements of bulk density and infiltration rate were not sufficiently precise to separate differences between lease and control soils.

In the second year, intensive sampling and laboratory analysis of bulk density, particle size, organic matter, and carbonate demonstrated statistically significant differences between lease and control soils at six of eight sites. Bulk density was shown to be highly quantifiable, precise, simple to measure, low cost, and intimately related to known properties governing soil structure. Particle size distribution, characterized by the geometric mean and standard deviation, was shown to be the most quantifiable and significant property underlying soil structure at these sites. The calculation of geometric mean and standard deviation from hydrometer measurements of particle size is simple and straightforward; the two parameters can also be estimated from clay, silt and sand percentages. There was measurable carbonate in all soils, and lease soils had more on average than off-lease soils.

Measured only in the third year, crop productivity data showed that control soils yielded significantly more than lease soils at three sites. The data support the hypothesis that lease sites were expected to be less productive than control soils because of structural limitations. However, crop measurements, on- and off-lease, were abnormally depressed because of drought. Repeated measurements done under more normal climatic conditions would be necessary as conclusive support for the hypothesis.

An electronic tiller (E-tiller) was developed and tested as a means making continuous field measurements of tillage resistance. Draft force (lbs.) was shown to be a more stable measure than power requirements (force x velocity). Draft force in surface soils did not vary significantly between lease and control. However, draft force in subsoils (8" depth) on-lease was much higher than off-lease at the same depth, indicating significant subsoil compaction on-lease.

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INTRODUCTION

In Alberta prior to 1983 there were few standards governing the salvage and replacement of topsoil on well sites proposed for reclamation certificates. Hence, in many cases topsoil was not conserved and not used during the reclamation process. On these sites a mixture of A, B, and C horizons remained on the surface after well completion. These soil mixtures were fertilized, cultivated, and seeded with the expectation that the subsurface materials would be transformed into topsoil over time. Frequently, manure was added to the soil material on the surface in an attempt to change the surface structure and to provide organic matter and nutrients during its long decomposition period.

Not all of the reclamation attempts on these pre-1983 wellsites were entirely successful. In some cases, the surface structure of the exposed soil materials is evidently inferior to that of the surrounding agricultural lands. In various sites it is possible to see differences in plant abundance and crop vigor, standing water on compacted zones, large clods that do not break down between summer, winter and spring, and some farmers report higher power requirements during cultivation.

Since 1983 Alberta Environment has required that wellsite operators remove, store, and replace topsoil as a part of the reclamation process. Any problems of soil structure which occur as a result of removing and replacing topsoil are vastly different than those associated with wellsites developed prior to 1983. The questions germane to the development of soil structure on sites without topsoil replacement are:

- Do surface soils on wellsites develop structure similar to nearby control areas?
- Are 30 years enough time to develop structure like the surrounding soils?
- Does added organic matter, in the form of manure, persist in reclaimed soils and affect structure?
- Do increased clay contents in surface horizons lead to structural improvement or worsening?

- Can changes in clay, organic matter, carbonates, or other fundamental properties, be used as a surrogate for measurements of changes in soil structure?
- What is an adequate measure of soil structure on wellsites when the intention is to compare it to surrounding, undisturbed land?
- Are the existing field methods sufficiently quantitative to evaluate whether structures are equal?
- Does soil variability make it necessary to switch from field methods to laboratory analysis?
- Are there laboratory methods that could be transformed into acceptable field methods?
- Are there other ways of making field measurements of soil structure that overcome the limitations of variability?
- What is the relation between changes in soil structure and soil management requirements, such as power requirements for tillage and the timing of tillage, seeding, and harvesting.
- What is the relationship of soil structure to plant productivity?

The questions fall into three general categories: i) How can structure be measured so that soils and treatments can be quantitatively compared? ii) Are there differences in structure and the underlying properties between wellsites reclaimed without topsoil 30 years ago and the surrounding lands from which the wellsites were taken? iii) How do measures of soil structure relate to plant growth or soil management practices?

One of the greatest challenges is to identify methods for measuring structure, not because it is novel, rather because so many have tried without coming to any agreement about which methods are most appropriate. There are comprehensive reviews covering the measurement of physical properties in reclaimed soils (Naeth et al. 1991), most of which might be considered to be indicators of soil structure, but there is no agreement about which kind of measurement, or even how to make a given measurement. Focusing attention on variability and the interplay between method and statistically meaningful comparisons is one way of recasting the debate on the measurement of soil

structure. There is no value in reporting information on any property, including structure, which does not give some estimate of precision or its reliability (Freese 1962). This study undertakes the measurement of several aspects of soil structure with the goal of comparing reclaimed wellsites to surrounding areas. We begin by using traditional pedological observations and simple measurements in the field. The purpose is to base our investigations on time-honored methods so that comparisons can be made to other investigations using the same methodology. Furthermore, some of the methods are semi-quantitative and lend themselves to rapid, inexpensive replications that could be statistically based. We also measure in the first phase under field conditions several fully quantitative properties directly associated with soil structure: bulk density using the core method, aggregate size by sieving, and infiltration rate, a complex structure-related property with a sound mathematical basis but usually subject to wide variability. In the second phase we take our measurements to the laboratory. For purposes of characterizing structure we focus on bulk density using the clod method and aggregate size based on a minimum of 10 size fractions. Concurrently, we measure the underlying soil properties most closely associated with structure – particle size, organic matter, and carbonates. The second phase explores the possibility of adapting commonly accepted measures of structure to more rigorous analytical conditions to reduce experimental error and increase precision, and thereby justify quantitative assessments of similarities and differences. We also propose a radically different way of expressing particle size, omitting discussion of clay, silt and sand, as a means of characterizing the most important physical property of soils and explaining changes in structure. In the third phase, we discuss the development and application of tillage resistance using a newly invented "electronic tiller" or E-tiller, a new field-based method for evaluating structure. In the end, we are searching for measurements that are quantitative and statistically sound even in the face of extreme variability.

The juxtaposition of field and laboratory measurements of soil structure arises from consideration of accuracy, precision, variability, cost, interpretability, and availability. There is no simple way of choosing between field and lab, except by considering the purpose of the investigation, the nature of soils, the contrast in treatments under

comparison, and the performance of the methods under consideration. It is the latter aspect that undergoes continual improvement and to which we would like to contribute. Any improvement we make will serve as a platform for further development of better methods for measuring structure in the future. By combining field and lab methods, we are searching for synergies that lead to more precision, lower cost, and better interpretation.

The questions about the development of structure on wellsites over time initiated this project. We digressed into questions of measurement and methodology only because there are no widely accepted models for quantitatively comparing soil structure. Our aim is to return to the central question of whether wellsites without topsoil evolve into similar soils as those from which they arose. We might find that some soils regain structure and others don't. More importantly, we may discover why some soils regain structure while others follow a different trajectory. The question of whether we can manage soils without topsoil to an acceptable structural condition has important economic implications. Topsoil removal and replacement is expensive. If it is easy to convert subsoil or subsoil mixed with topsoil into the full equivalent of the original topsoil, the expense of topsoil salvage could be directed to other environmental or production bottlenecks. If we find that some soils can be beneficially transformed, that structure can be improved, we will have new management tools available for wide use in land management. If, on the other hand, we find that soils undergoing topsoil removal continue to degrade over time from a structural point of view, we'll know that the protection of surface soil structure is paramount.

The third set of questions deals with the relationship of soil structure to plant performance and soil management options. This is the central question of researcher (Naeth et al.) and field practitioner alike. Their question might be rephrased: "At what point does soil structure impede plant growth or cause a change in soil management costs or practices?" Many studies, even some focusing on reclaimed soils in Alberta (Thacker et al. 1994) have been done on plant root response to changes in bulk density. Others have measured plant response to changes in soil penetration resistance (Barley

et al. 1965) or changes in macroporosity as reflected in soil aeration (Glinski and Stepniewski (1985). But the complex interaction of soil structure and plant response, especially under field conditions, makes field-testing an on-going requirement.

Evaluating changes in soil management practices by using the response of tillage equipment to changes in soil structure is relatively new (Jones 1987, van Bergeijk et al. 2001). In fact, tillage resistance can be used in two ways: i) as a dynamic, spatial measure of soil structure in the field, and ii) as a response to changes in soil structure measured in other ways. The advancements in inexpensive electronics for data gathering and data synthesis make continuous field measurements a promising area of new development. We might not be able to give definitive answers about the intricate relations of plant growth to changes in structure, but estimates of soil behavior and its variability as measured by tillage equipment are likely to appear soon.

This main body of this report is divided into three stages:

1. Phase 1: Site and Field Investigations. We locate the wellsite leases and describe in a general way their soils, vegetation, and landform. We present information on soil chemical and physical properties as measured at the time of reclamation and certification (pre-1982). We re-examine these sites, record profile descriptions, on- and off-lease, and make new measurements of structure-related properties.
2. Phase 2: Laboratory Investigations. We return to the lease sites across the province and collect soils on an intensive sampling grid. We conduct laboratory analyses of bulk density and aggregate size and relate them to fundamental properties of the particle size distribution (not just textural classes), organic matter and carbonate.
3. Phase 3: Tillage Resistance and Vegetation Response. We design and build a prototype of an "electronic tiller" to make continuous measurements of tillage resistance. We test the E-tiller in the field at five lease sites and surrounding areas. We design a crop sampling strategy to evaluate the relationship of soil structure to difference in plant productivity, but an

abnormally dry year at the end of a four-year drought cycle severely curtails the measurements and interpretation.

The products of this research project could benefit all who work in soil reclamation--government, industry, consultants, and researchers--by establishing quantitative approaches to the evaluation of soil structure. This research contributes to the establishment of measurement standards that will allow rigorous comparisons of the effect of reclamation practices on surface soil structure. Finally, this research might lead to the development of new methods for quantifying soil structure in the field.

1. PHASE 1. SITE AND FIELD INVESTIGATIONS

1.1 Introduction

In the early 1980s, Alberta Environment (Reclamation Branch) initiated a monitoring program to assess their reclamation program on reclaimed wellsites, pipelines and battery sites. The monitoring program assessed 69 wellsites, 29 pipelines, and 4 battery sites. Of these, eight wellsites were selected for use in the current study. These were chosen using the following criteria:

- a history of deficiencies in soil physical properties (e.g. reduced organic matter content or increased clay content) in comparison with adjacent non-wellsite area,
- soil physical properties were the primary limitation on site productivity (i.e. soil chemical deficiencies were avoided),
- manure application to mitigate on-site soil deficiencies was recommended by the Alberta Environment land reclamation specialist in the early 1980s, and
- soil physical and chemical analyses done in the early 1980s were available for control and wellsite locations.

Phase 1 includes site selection, a review of existing information at each site, and field measurement of surface structure.

1.2 Materials and Methods

1.2.1 *Sites*

We chose eight sites in accordance with the criteria listed above. The wellsites and control areas were described with respect to landscape or landform, topography, hydrological features, and crops or dominant vegetation cover. In addition, we drew a map of each site, marking the wellhead, the boundaries of the lease, and the sample points.

1.2.2 *Soil description*

We described two soil profiles at each location: one on the wellsite and one in the control area. The soil pit locations were chosen to be as representative as possible. The wellsite

pit usually occurred within 10 or 20 m of the wellhead. The location of the control area pit was always within 50 m of the lease boundary and chosen to represent a soil type predominant in the area. Soil pits were excavated to ~1 m depth so that all major horizons were exposed. Table 1.1 lists the soil properties described or measured in each pit.

Table 1.1. Soil properties described or measured in the field

Horizon	Depth[1] Distinctness
Colour	Matrix • Moisture state • Location
Ped & Void Surfaces	Kind Amount
Texture	Hand texture
Structure	Type Grade Size
Pores & Cracks	Shape Size Quantity
Roots	Location Size Quantity
Consistence	Rupture resistance Penetration resistance (pocket penetrometer) Surface crusts Cementing agents Manner of failure • Brittleness • Fluidity • Smeariness

[1] All measurements following Schoeneberger et al. 1998.

1.2.3 *Field tests*

We made triplicate measurements of soil aggregate size and two kinds of infiltration rates on the wellsite and in the control area at each location. Aggregate size distribution was measured by sieving the whole soil sample through screen sizes of 2 mm, 5 mm, and 10 mm. Each sieve fraction was dried and weighed separately. We used a double ring infiltration method (Grossman 2000) to measure short-term (5 min) and long-term (2 to 4 hrs) infiltration rates. The outer ring, 60 cm diameter and 20 cm high, was

inserted 5 cm into the soil, filled with water, and left to drain into the soil overnight. The next day a 15 cm ring, 30 cm high, was inserted 5 cm into the wet soil approximately in the centre of the outer ring. A plastic pouch was laid inside the inner ring to protect the soil surface from disturbance, and then 885 mL of water were poured into the plastic pouch. The water was emptied from the pouch carefully to protect the soil surface and instantaneously to provide an infiltration initiation time. After the water had drained completely, or 1 hr, whichever was shortest, the infiltration procedure was repeated. This time the water was allowed to drain exactly 5 min and the remaining water was removed by a hand suction pump (syringe) and its volume was measured. If the water drained from the inner ring in less than 5 min, the exact time of drainage was noted. Short-term infiltration rates were calculated according to Equation 1.

Equation 1

$$\text{Infiltration} = \frac{\text{Volume water in (cm}^3\text{) - Volume water out (cm}^3\text{)}}{126.7\ \text{cm}^3/\text{hr}\left[\frac{\text{Time elapsed (min)}}{60\ \text{min/hr}}\right]}$$

Long-term infiltration was measured using the same set-up, following the short-term test. Eight hundred eight five milliliters of water were emptied from the plastic pouch within the inner ring. We timed the complete drainage of water from the inner ring unless it exceeded 4 hrs. In that case, we noted the drainage time and measured the amount of remaining water. Long-term infiltration rates were calculated according to Equation 1 also.

1.2.4 *Bulk density and undisturbed core sampling*

We excavated a large (7.6 cm diameter, 3.0 cm depth) undisturbed core sample from each infiltration sample location. Each core sample was carefully pared so that the soil exactly fit the confining ring. The soil in the larger core was emptied into a paper bag, weighed and dried in the laboratory, and used to calculate bulk density (Blake and Hartge 1985).

1.3 Results

1.3.1 *Sites*

The sites are distributed across central Alberta from east to west (Figure 1.1). All sites are have Chernozemic soils formed on glacial till parent materials. The ecological regions vary from parkland to mixed grass prairie in the east (Hayter sites) and southern portion (Olds site) of the sampled area. The Rimbey site is in a mixed wood vegetation zone. Most sites are flat (sometimes due to the need to level the site mechanically to situate the drilling rigs). Hayter 2 is situated on a west-facing slope of approximately 4%. None of the sites were wet or had standing water at the time of sampling. Only the Ranfurly site has a water table near the surface, although one of the control locations for the Vermilion site showed severe mottling at 40 cm depth, indicating poor drainage and maybe the presence of a water table. The general state of dryness can be attributed to the lengthy drought period most of Alberta has undergone since the winter of 1999 - 2000. We selected sites with a wide range of crops--canola, wheat, barley, and several forage or pasture areas. The Vermilion site is planted to forage now but this site was cleared from forested areas when the lease was developed. Hence, vegetation on the control areas is different than that on the wellsite.

1.3.2 *Prior characterization of wellsites*

Table 1.2 summarizes information on the chemical and physical properties of all sites, on- and off-lease, as measured shortly after reclamation (more than 30 years ago). The pH values range from 6 to 8.4 and electrical conductivity is low in all cases. Sodium adsorption ration (SAR) varies from near zero to 20, indicating that the Chipman and Ranfurly lease areas are sodic. Organic carbon is consistently higher is soils of the surrounding area than those on the wellsite leases. Clay increases on lease soils compared to the surrounding area.

Site Name*	Soil Group	Natural Subregions	Landform	Topography	Vegetation
Hythe	Dark Grey Chernozem	Peace River Parkland	Glacial till plain	Flat (<1% slope)	Annual crops & forage
Chipman	Black Chernozem	Central Parkland	Glacial till (sodic)	Flat, high watertable	Long-term pasture
Ranfurly	Black Chernozem	Central Parkland	Glaciofluvial-lacustrine	Lease is flat ~ 2 m above lake, hilly off-	Annual crops
Vermilion	Black Chernozem	Central Parkland	Glacial moraine	Very hilly (wellsite flat after hilltop removed)	Wellsite in bromegrass, surrounded by poplar.
Hayter 1	Dark Brown Chernozem	Mixedgrass	Eolian on glacial till	Flat to undulating	Annual crops
Hayter 2	Dark Brown Chernozem	Mixedgrass	Glacial till	3% slope)	Annual crops
Rimbey	Dark Grey Chernozem	Dry Mixedwood	Gacial till plain	Flat (<1% slope)	Annual crops
Olds	Black Chernozem	Central Parkland	Glacial till plain	Flat, slight depressions	Annual crops

*Sites named after nearest town or village in Alberta.

Figure 1.1. Location of lease sites and information on soils, vegetation and land form

Table 1.2. Chemical and physical properties of eight wellsites, including data on- and off-lease at two depths from Alberta Environment records (1981 – 1983)

Site	Location	Depth	Parameters										
			pH	EC	SAR	Cations			Organic C	Particle Size			Saturation
						Ca + Mg	Na	K		Sand	Silt	Clay	
				(dS/m)		(me/L)			(%)		(%)		(%)
Hythe	Lease	0-6"	7.0	4.1	2.0	53.5	10.4	0.2					59
	Lease	6-12"	7.2	3.7	1.9	49.3	9.2	0.3					64
	Off-Lease	0-6"	6.4	2.1	0.7	34.8	2.6	0.2					65
	Off-Lease	6-12"	6.4	1.5	0.8	20.0	2.3	0.1					53
Chipman	Lease	0-6"	7.7	5.2	8.7	39.5	39.0	0.2	2.3	50	27	23	65
	Lease	6-12"	7.7	5.8	5.7	41.2	44.4	0.2	1.6	46	26	28	74
	Off-Lease	0-6"	6.8	0.6	2.3	6.0	3.3	0.1	3.7	61	30	9	57
	Off-Lease	6-12"	7.1	2.7	5.7	19.0	25.1	0.2	2.3	55	27	18	52
Ranfurly	Lease	0-6"	8.4	2.1	18.6	3.2	21.9	0.2	2.3	56	25	19	64
	Lease	6-12"	8.6	2.5	19.8	3.5	26.6	0.2	2.1	52	27	21	60
	Off-Lease	0-6"	7.4	0.8	5.3	3.3	6.8	0.2	5.2	62	26	12	49
	Off-Lease	6-12"	7.8	1.2	7.2	4.2	10.4	0.2	4.5	61	25	14	43
Vermilion	Lease	0-6"	7.1	1.6	3.2	11.2	7.3	0.3	4.3	48	31	21	51
	Lease	6-12"	7.5	1.1	2.1	9.0	4.4	0.2	2.0	42	29	29	60
	Off-Lease	0-6"	6.2	0.8	0.4	9.0	0.8	0.5	7.8	51	27	22	64
	Off-Lease	6-12"	6.2	0.5	0.3	5.5	0.5	0.3	3.8	43	28	29	51
Hayter 1	Lease	0-6"	6.8	1.0	0.8	13.6	2.1	0.6	1.7	64	22	14	40
	Lease	6-12"	7.1	1.4	1.0	20.8	3.2	0.7	1.6	55	21	24	43
	Off-Lease	0-6"	6.1	1.8	1.1	23.1	4.2	0.5	2.5	58	28	13	48
	Off-Lease	6-12"	6.3	1.4	1.4	23.8	4.2	0.3	1.7	53	25	22	44

Table 1.2. Chemical and physical properties of eight wellsites, including data on- and off-lease at two depths from Alberta Environment records (1981 – 1983) (Cont'd.)

Site	Location	Depth	Parameters										
			pH	EC	SAR	Cations			Organic C	Particle Size			Saturation
						Ca + Mg	Na	K		Sand	Silt	Clay	Ca + Mg
				(dS/m)		(me/L)			(%)	(%)			(%)
Hayter 2	Lease	0-6"	7.1	0.6	0.7	6.8	1.2	0.2	2.2	44	30	26	56
	Lease	6-12"	7.3	0.5	1.4	4.3	2.2	0.1	1.8	33	25	42	58
	Off-Lease	0-6"	6.7	0.7	0.2	9.0	0.5	0.2	2.0	42	42	16	57
	Off-Lease	6-12"	6.8	0.5	0.3	7.6	0.7	0.1	1.6	37	39	24	54
Rimbey	Lease	0-12"	6.9	3.1	7.4	4.2	10.4	1.3	2.8				
	Lease	12-20"	6.3	3.0			30.8						
	Off-Lease	0-12"	6.3	0.3	1.3	0.6	0.8	0.3	3.9				
	Off-Lease	12-20"	6.4	0.8			0.9						
Olds	Lease	0-6"	4.9	1.7	6.4	8.2	10.7	0.2	1.4	43	35	22	49
	Lease	6-12"	7.7	1.7	3.7	11.5	8.4	0.2	0.8	40	34	26	50
	Off-Lease	0-6"	7.5	0.6	0.6	5.7	1.0	0.2	4.0	44	42	14	81
	Off-Lease	6-12"	7.7	0.4	0.5	4.7	0.8	0.1	2.7	40	41	19	63

1.3.3 *Current field description of soil properties*

From one sampling location on the wellsite and one in the control area, we compared soil profile descriptions (Table 1.3).

In general, the changes resulting from lease development and reclamation are:

- decrease in depth of topsoil (A horizon)
- change in colour value and chroma, but not often a change in hue
- change in structure type (often granular to subangular blocky or even the development of prismatic or massive types) and structure grade (mostly an increase in firmness or hardness), but seldom a change in structure size
- almost no change in root size or quantity
- moderate to severe increases in rupture resistance, and
- moderate to severe increase in penetrometer resistance.

There are exceptions to all the generalizations listed above when each horizon is compared between wellsite and control area. Most apparent, however, is the tendency for reclaimed lease soils to become harder (firmer) than those in the control areas.

1.3.4 *Soil physical properties as measured in the field*

The soil physical properties measured in the field were: aggregate size distribution, bulk density, water infiltration rate, and texture class (Table 1.4). Although texture was hand-measured in the field, the classification reported in Table 1.4 arises from the laboratory measurement of particle size distribution.

The topsoil on every wellsite has an increase in clay content when compared to the control locations. In the case of the Rimbey site, the increase in clay content on-lease is dramatic--30% more than the control topsoil. Several sites show on-lease increases in clay content between 10 and 15%. Consequently, these sites also show a change in textural class when contrasting wellsite and control soils.

Table 1. 3. Soil profile description from field investigations in 2000

Site	Treatment	Horizon	Depth	Colour	Structure			Roots		Consistence	
					Type	Grade	Size mm	Size mm	Quantity cm^{-2}	Rupture Resistance	Penetrometer MPa
Rimbey	Wellsite	A	0-15	10 Yr 3/2	GR	Mod.	<1-2	<1	1-5	Mod. Hard (m)	4.5
		B	15-33	10 Yr 5/2	PR	Strong	20-60	<1	>5	Mod. Hard (m)	4.0
	Control	A	0-15	75 Yr 3/1	GR	Mod. Strong	1-5	<1	>5	Friable	3.0
		B	15-28	2.5 Yr 4/3	SBK	Mod. Strong	5-10	<1	1->5	V. Friable - Friable (m)	3.5
Olds	Wellsite	Ap	0-11	10 Yr 2/1	GR	ND	ND	ND	>5	Friable - Firm	ND
		AB	11-18	10 Yr 3/2	PL	ND	ND	ND	ND	Hard - Very Hard	ND
		B	18-32	10 Yr 4/2	PL - ABK	ND	ND	ND	1-2	V. Hard	ND
		C	32-40	10 Yr 6/3	PL - ABK	ND	ND	ND	<1	Friable	ND
	Control	A	0-20	10 Yr 3/1	GR	Mod.	<1-2	1-2	>5	V. Friable (m)	ND
		AB	20-30	7 Yr 3/1	PL-ABK	Weak	<1	1-2	>5	Friable (m)	ND
		B	30-40	10 Yr 5/6	PL-ABK	Mod.	1-2	1-2	>5	Friable (m)	ND
Hythe	Wellsite	Ap1	0-7	10 Yr 3/2	GR - SBK	Mod.	ND	ND	>5	Firm (m)	2-0
		Ap2	7-17	10 Yr 3/2	SBK	Strong	ND	ND	>5	Rigid (m)	>4.5
		B1	17-40	10 Yr 4/2	GR - SBK	Strong	100-500	ND	<1	Rigid (m)	4-4.5
		B2	40+	10 Yr 4/1	PL	Mod.	>50	ND	<1	Very firm (m)	4-4.5
	Control	Ap	0-21	10 Yr 2/2	ABK	Mod.	ND	ND	>5	Very friable	1.0
		AB	21-26	10 Yr 4/2	ABK	Weak Strong	2-5	ND	>5	Friable	3.0
		Bt1	26-38	10 Yr 4/2	PR	Strong	50-100	ND	>5	Friable	4.5
		Bt2	38-64	10 Yr 4/2	SBK	Mod.	20-50	ND	>5	Friable	4.5
Hayter 1	Wellsite	Ap	0-8	10 Yr 3/2	SBK	Weak	<5	<1	1-5	Friable	1.0
		AB	8-18	10 Yr 4/2-6/2	PL - WDG	Mod Strong	>10	<1	1->5	Firm	3.5
		B1	18-39	10 Yr 4/3	MASS	Structureless	>50	<1	<1	Firm	3.5
		B2	39-97	10 Yr 4/2	ABK	Strong	10-20	<1	1-5	Friable	2.5
	Control	Ap	0-18	10 Yr 3/1	SAB	Mod	ND	<1	>5	Friable-firm	2.5
		AB	18-37	10 Yr 3/3	SAB	Mod	>50	<1	1-5	Friable	1.5
		BC	37-65	10 Yr 6/4	SBK	Mod	>50	<1	1-5	Friable	1.5

Table 1.3. Soil profile description from field investigations in 2000

Site	Treatment	Horizon	Depth	Colour	Structure		Roots			Consistence	
					Type	Grade	Size	Size	Quantity	Rupture Resistance	Penetrometer
							mm	mm	cm^{-2}		MPa
		C	65-90+	10 Yr 6/3	SBK	Mod	>50	<1	1-5	Friable	1.5
Hayter 2	Wellsite	Ap	0-9	10 Yr 3/2	GR - SBK	Weak	ND	<1	1-5	Firm	2.5
		B1	9-15	ND	PL	Mod	>10	<1	1-5	Firm	2.5
		B2	15-60	ND	SBK	Mod	10-50	<1	1-5	Firm	3.0
		C	60+	10 Yr 5/3	SBK	ND	10-50	<1	<1	Firm	ND
	Control	Ap	0-25	10 Yr 3/1	GR	Weak	ND	<1	>5	Friable	1.5
		AB	25-42	10 Yr 3/3	ABK	Mod	>50	<1	>5	Friable firm	1.5
		BM	42-67	10 Yr 4/2	PR - SBK	Mod-Strong	50-100	<1	1-5	Firm	2.0
		C	67+	10 Yr 5/3	PR - SBK	Mod-Strong	20-50	<1	<1-5	Friable	ND
Vermilion	Wellsite	Ah	0-6	10 Yr 4/2	SBK - GR	Strong	<5-10	1-2	>5	Mod Hard (d)	3-5
		IB	6-16	10 Yr 3/3	SBK	Strong	5-20	1-2	>5	Hard (d)	4-5
		IIB	16-50+	10 Yr 3/2	PR - ABK	Strong	5-50	1-2	>5	Friable (m)	4.0
	Control	Ah	0-22	ND	GR	Strong	<1	1-10	>5	Mod Hard (d)	1.0
		B	22-50+	ND	SBK - GR	Mod-Strong	<5-10	2-10	1-5	Hard (d)	4
Ranfurly	Wellsite	Ap	0-4	10 Yr 3/2	PL	Strong	>10	1-2	>5	ND	ND
		AB	4-26	2.5 Yr 4/3	ABK	Mod	5-10	1-2	1-5	ND	ND
		B	26+	2.5 Yr 5/6	ABK	Weak	5-10	1-2	<1	ND	ND
	Control	Ap	0-20	10 Yr 2/1	SBK	Weak	5-10	<1	>5	Friable (m)	1.5
		Ah	20-37	10 Yr 2/1	SBK	Weak	5-10	<1	>5	Friable (m)	1.5
		Btj	37-43	10 Yr 4/3	PR	Weak	5-10	<1	1-5	Friable (m)	2.5
Chipman	Wellsite	A	0-30	10 Yr 3/2	ABK - PL	Mod	<5->50	<1	>5	Ext Firm - Firm	>4
		Bt	ND	ND	ND	ND	10->50	ND	1-5	Very Firm	>4
		BC	ND	10 Yr 3/2	ABK	ND	>50	<1	1-5	Very firm	>4
	Control	Ap	0-15	10 Yr 4/2	ABK	Weak	5-20	<1	>5	Friable	>4
		Ac	15-18	10 Yr 6/3	PL	Weak - Mod	1-2	<1	>5	Very Friable	>4
		AB	18-21	10 Yr 5/3	PL - SBK	Mod	10-50	<1	>5	Firm	>4
		Bt	21-55	10 Yr 5/3	SBK	Strong	5-20	<1	>5	Firm	2.5

Table 1.3. Soil profile description from field investigations in 2000

Site	Treatment	Horizon	Depth	Colour	Structure		Roots			Consistence	
					Type	Grade	Size mm	Size mm	Quantity cm^{-2}	Rupture Resistance	Penetrometer MPa
St. Paul	Wellsite	A*	0-4	ND	GR	Mod	1-5	1-2	>5	ND	>4.5
		AB	4-14	ND	ABK - PR	Strong	5-20	1-2	1-5	ND	>4.5
		B	14-40	ND	PR - COL	Strong	5-10	1-2	1-5	ND	>4.5
	Control	Ah	0-15	ND	GR	Mod	<1	2-5	2-5	ND	ND
		Ac	15-18	ND	GR	Stless - Weak	<1	2.5	2.5	ND	ND
		Bnt	18-61	ND	COL	Strong	20-50	1-2	2-5	ND	ND
Entwistle	Wellsite	A + LFH	0-13	7.5 Yr 3/2	ABK - WEG	Mod	<5-20	<1	>5	Very Firm	2.5
		B	13-29	10 Yr 4/1	ABK-WEG	Mod	10-20	<1	>5	Very Firm	1.5
		BC	29+	10 Yr 5/1	ABK	Mod	10-20	<1	>5	Firm	0.5
	Control	Ah + LFH	0-13	10 Yr 2/1	GR	Weak	1-5	<1	>5	Very Friable	0.5
		Ac	13-20	10 Yr 4/1	PL	Weak	2->10	<1	1->5	Firm	2
		Bt	26+	10 Yr 5/3	GR	Mod	>10	<1	<1	Friable	1

Table 1. 4. Site and soil A horizon data from field investigations in 2000

Location	Treatment	Particle Size Distribution			Textural Class	Aggregate Size Distribution (mm) % Total Mass, Dry				Bulk Density g cm^{-3}	Infiltration Rate cm hr^{-1}	
		Sand	Silt	Clay		<2	2-5	5-10	>10		Short	Long
		%										
Rimby	Wellsite	32	21	47	Clay Loam	12	9	13	66	1.27 (0.15)*	5.0 (1.9)*	0.9 (0.2)*
	Control	28	55	17	Silt Loam	24	15	17	44	1.21	9.0 (4.6)	2.6 (1.8)
Olds	Wellsite	35	45	20	Loam	-	-	-	-	0.88 (0.15)	20.8 (12.6)	9.7 (10.7)
	Control	33	48	19	Loamy Sand	27	18	21	34	0.87 (0.12)	9.9 (5.3)	3.5 (2.3)
Hythe	Wellsite	15	49	36	Silt Clay Loam	36	21	23	20	1.12 (0.06)	35.6 (35.1)	17.4 (18.2)
	Control	23	52	25	Silt Loam	22	34	20	24	1.00 (0.15)	13.4 (1.9)	4.0 (0.7)
Hayter	Wellsite	57	24	19	Sandy Loam	45	13	15	27	1.32 (0.23)	8.3 (6.4)	3.1 (0.9)
	Control	68	16	16	Silt Loam	37	19	18	27	1.41 (0.14)	6.2 (7.0)	1.7 (1.8)
Hayter	Wellsite	23	43	34	Clay Loam	17	12	15	56	1.10 (0.04)	26.0 (36.3)	13.4 (21.4)
	Control	29	45	27	Clay Loam	26	17	16	41	1.05 (0.07)	17.7 (9.6)	3.6 (1.5)
Vermilion	Wellsite	38	35	27	Clay Loam	30	14	16	39	1.06 (0.40)	3.3 (2.4)	1.1 (0.8)
	Control	45	37	19	Loam	45	10	8	37	1.26 (0.15)	43.5 (40.3)	19.5 (28.6)
Ranfurly	Wellsite	60	24	16	Sandy Loam	39	13	15	32	1.39 (0.20)	2.1 (0.3)	0.7 (0.04)
	Control	72	17	12	Sandy Loam	51	24	19	5	1.26 (0.21)	12.0 (9.1)	5.9 (6.4)
St. Paul	Wellsite	47	27	27	Sand Clay Loam	8	10	22	59	1.46 (0.10)	12.0 (8.9)	1.7 (1.7)
	Control	49	35	17	Loam	38	19	11	31	1.32 (0.06)	14.6 (15.2)	2.1 (2.5)
Chipman	Wellsite	39	35	26	Loam	14	11	13	62	1.50 (0.08)	4.6 (2.4)	0.8 (0.2)
	Control	56	29	16	Sandy Loam	58	8	7	26	1.44 (0.07)	5.6 (4.1)	2.3 (1.0)
Entwistle	Wellsite	20	40	40	Clay Loam	2	4	8	86	1.42 (0.33)	0.2 (0.3)	0.1 (0.04)
	Control	18	57	26	Silt Loam	4	8	9	78	1.34 (0.21)	19.0 (21.0)	8.4 (8.6)

Particle size distribution also distinguishes clearly between wellsite and control soils. However, as was the case in aggregate size distribution data, we measured only one replicate per treatment (wellsite vs. control) per site, and therefore we cannot speak to the issue of variability.

The data describing aggregate size distribution of topsoils from wellsites and control areas are shown in Table 1.4. This data is presented graphically in Figure 1.2. Five of eight sites show marked increases (>20%) in large aggregates when comparing control to wellsite topsoils. The control topsoil on the Chipman site, for example, has 58% of its aggregates <2 mm diameter and 26% of its aggregates are >10 mm diameter, while the wellsite soil shows almost the complete reversal in these percentages by size class. Only Hayter 1 site has a decrease in large aggregates when control soil is compared to wellsite soil.

Aggregate size classes tend to differ greatly between reclaimed wellsite soils and control areas. We measured only one replicate of reclaimed and control surface soils per site in this study, and therefore cannot make statements about statistical differences in this characteristic. The simplicity of measuring aggregate distribution in the field makes it a promising candidate for the routine monitoring of structural differences and development. There is a need to standardize the comparison of aggregate size distribution data in a form that allows specific hypothesis testing. Furthermore, the relationship between changes in aggregate size distribution and soil behavior has not been defined.

In almost all cases the bulk density of the wellsite topsoil is apparently higher than the bulk density of control soils (Table 1.4). Bulk density measurements are averages of 3 replicates (with a few exceptions), and the variability of bulk density measurements, as expressed by the standard deviation, is high enough to prevent the conclusion that wellsites have higher bulk densities than control soils.

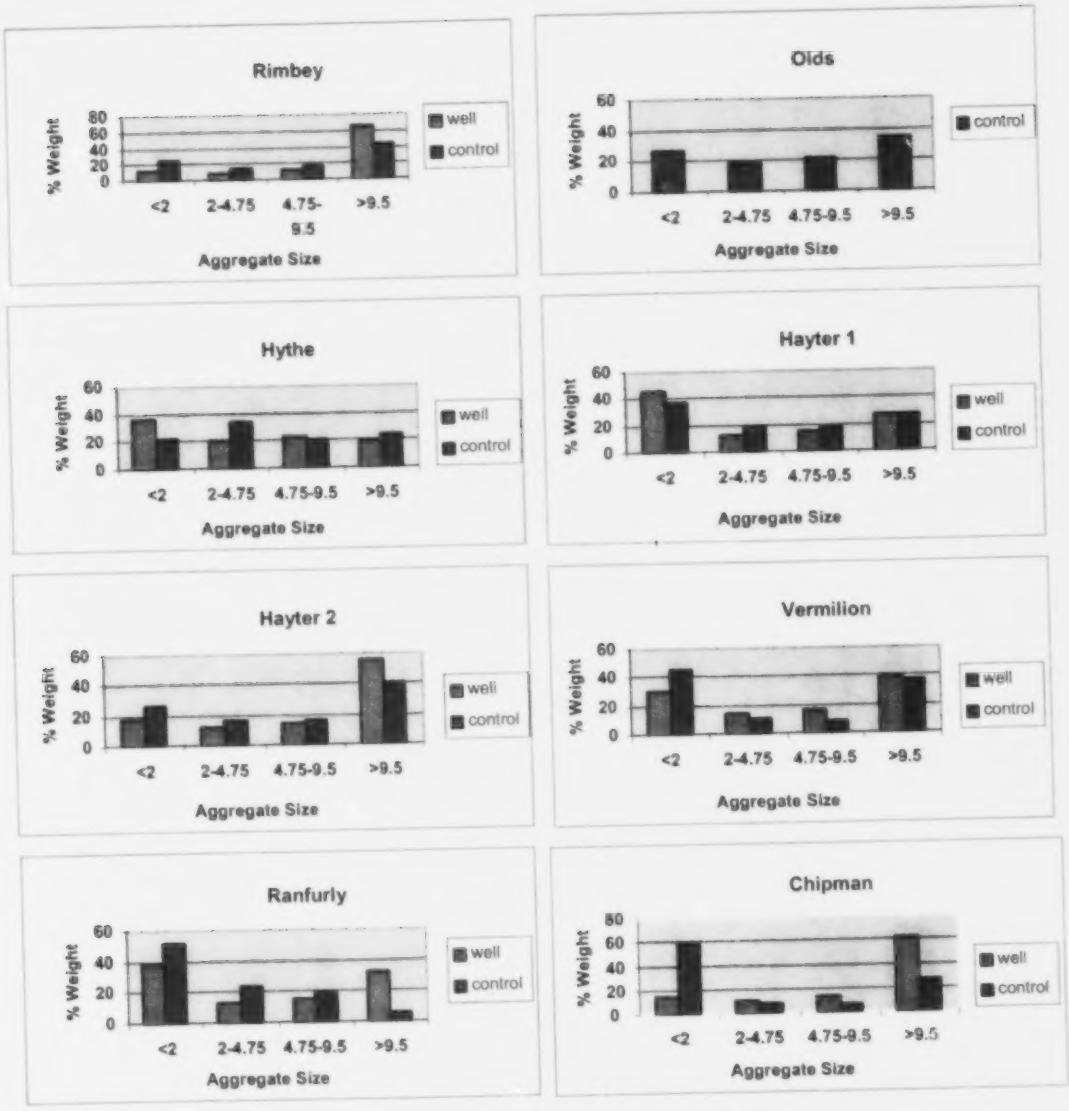

Figure 1.2. Size distribution of various aggregate fractions (well vs control) by site

Bulk density is perhaps the most common field measure of soil structure. We exercised special caution in collecting bulk density samples to prevent variation due to sampling procedure. Even then, the natural variability of this physical property covered up all reported differences in mean values. We would have to collect many bulk density samples in each treatment (wellsite vs. control) to separate averages on a statistical basis.

The same argument applies to a comparison of short- and long-term infiltration rates on wellsites and in control areas (Table 1.4). If there are significant differences in infiltration rates between control and wellsite locations, we have not succeeded in measuring them with only three replications.

Standard deviations equaled or exceeded the mean values, making a formal analysis of statistical differences unnecessary. Infiltration rates varied more than bulk density values, thus signifying that more than 25 replicates would be needed to establish statistical differences.

2. PHASE 2. LABORATORY MEASUREMENTS

2.1 Introduction

The goal of this project is to decide whether surface soils on wellsites in Alberta reclaimed before 1983 develop structure similar to that of nearby control areas. The basis of the decision is a comparison surface soil structure on- and off-wellsite for a variety of locations within the Province (Figure 1.1). Investigations at eight sites in the summer and fall of 2000 showed that soil aggregates on wellsites had higher rupture resistance, penetration resistance, and were larger in size than aggregates taken from surrounding farmland. All of these results indicate that soil structure on wellsites has not returned to its pre-disturbed state even with the passage of 30 years or more. However, the most important finding of studies conducted in 2000 was that all measures of soil structure on all sites were extremely variable, thereby making it impossible to quantify the differences between wellsites and surrounding farmland.

The overall objective of Phase 2 to be carried out in 2001 was to design and implement a sampling and analysis plan that would allow for statistical comparisons of soil structure between wellsite and surrounding farmland even under conditions of extreme variability. We adopted an intensive sampling program for wellsite and control areas, and adapted machinery, instrumentation, and methodology to measure a wide spectrum of soil characteristics related to soil structure.

2.2 Materials and Methods

2.2.1 *Site selection*

We sampled and analyzed soils from the same eight sites studied in Phase 1 & 2 (see Figure 1.1 for names, locations in Alberta, and general soil, vegetation and landscape information).

2.2.2 *Site delineation and sampling plan*

On each site we located the wellhead using a magnetic pinfinder (Schonstedt). We located and marked the boundaries of the wellsite by measuring distances from the wellhead using maps developed during drilling and reclamation. We placed nine

sample points in a grid around the wellhead. We placed another 16 samples on the wellsite in an expanded grid with the wellhead at the center. Consequently, each wellsite was covered with a 25-point sample grid. The distance between sample points on the grid varied between 5 to 7 m, depending on the size of the wellsite. The surrounding farmland (control area) was sampled by evenly distributing 20 to 25 sample points along the four outside boundaries of the lease.

2.2.3 *Soil sample collection and processing*

At each sample point we collected 3 to 5 kg of topsoil by digging a small circle (~30 cm diameter) to the depth of the interface between topsoil and subsoil and removing the excavated volume. Each soil sample was placed in a 5.5 L bucket and covered with bubble-insulation to protect it against disturbance during transport. All soil samples were carefully removed from their buckets and air-dried during a 7 to 14 day period on tables in a greenhouse. After drying the soil samples were placed in individual plastic trays (30 cm x 80 cm x 3 cm depth) and stored until processing.

2.2.4 *Particle size distribution*

The hydrometer method and sand separation by were used on soil samples crushed and sieved to <2 mm diameter. First, the soil particles were dispersed by combining approximately 40 g of soil with 400 mL distilled water and 50 mL Na-hexametaphosphate (50 g/L) and subjecting the combined suspension to 7 min of ultrasonic vibration[1]. The beaker containing the soil suspension was suspended in a larger beaker of cold water to ensure that the suspension temperature did not exceed 30° C during ultrasonification. The dispersed soil in suspension was then transferred to sedimentation cylinders, filled with distilled water to 1000 mL, and allowed to cool to room temperature overnight. Prior to taking hydrometer measurements the soil particles were re-suspended evenly throughout the sedimentation cylinders by placing a tight-fitting rubber plug in the cylinder and inverting it repeatedly, top to bottom, for 1 min. Hydrometer measurements were taken at intervals of 3, 10, 30, 60, 90, 120, and 1440 min. A blank cylinder without soil but treated identically in all other ways was

[1] Sonics and Materials Inc. Vibra Cell. Danbury, C.T. 400 W Microtip set at <35% power.

measured for hydrometer values and temperature at each interval. Following the final hydrometer measurement, corresponding to 24 hr, the soil suspensions were sieved through a 45 μm screen. The sand particles remaining on the screen were flushed with distilled water into a beaker and oven-dried (105°C). The sand was then dry-sieved into five size fractions and weighed. All calculations of particle size distribution follow Gee and Bauder (1986) and were calculated on an excel spreadsheet.

2.2.5 *Geometric statistical properties (μ_x and σ_x) of particle size distribution*

Mechanical analysis translates into useful information on the statistical properties of particle size distribution (Shirazi and Boersma 1984). The geometric mean (μ_x) and geometric standard deviation (σ_x) characterize quantitatively the entire distribution. The former is the average particle size; the latter describes the "spread" of the distribution or the amount of variability between the finest particles (clay) and the largest (sand). We calculated the geometric particle size mean (μ_x) and variance (σ_x^2) of each sample following Shiozawa and Campbell (1991):

$$\mu_x = \Sigma\, m_i \ln d_i$$

$$\sigma_x^2 = \Sigma\, m_i (\ln d_i)^2 - \mu_x^2$$

where m_i is the mass fraction in size class (i), and d_i is the associated diameter, and ln is the natural log. We calculated d_1 following Shirazi et al. (1988) as the geometric means between size classes. For example:

$$d_1 = \ln 2000 + \ln 1000/2$$

where d_1 is the first or largest size class, 2000 and 1000 are the upper and lower limits of the largest size class in micrometers (μm).

2.2.6 *Bulk density*

A single, undisturbed, large 'clod' or aggregate, 50 to 100 mL volume, was chosen from each soil sample and measured for bulk density using a modification of the paraffin method described by Blake and Hartge (1986). Uncoated soil aggregates were weighed in air by suspending them in a nylon net cut to hold the soil sample as in a basket. The soil inside the nylon net was then dipped and removed immediately from molten paraffin wax. The paraffin hardened immediately and the soil aggregate was removed

from the nylon net. A single thread was tied around the coated aggregate and the aggregate was then dipped again in the molten paraffin wax to ensure full coating of the aggregate. The coated aggregate was weighed in air and then weighed while just immersed in water. Bulk density was calculated according to Blake (1965).

The soil within the aggregate measured for bulk density was used to measure total carbon, carbonate, particle size distribution, and moisture content for all samples from the Chipman, Hayter 1 & 2, and Olds sites. In these cases, the wax was peeled from the coated aggregate and the soil was hand-crushed using a mortar and pestle to <2 mm diameter. For those analyses requiring smaller particles, such as total carbon and carbonate, the hand-crushed soil was sieved to <100 μm diameter. In the case of the Hythe, Ranfurly, Vermilion and Rimbey sites, soil samples other than those used to measure bulk density were hand-crushed and sieved to the appropriate size for analysis of total carbon, carbonate, particle size distribution, and moisture content.

2.2.7 *Total carbon*

Measurements were done using a LECO Model CR-412 total carbon analyzer utilizing resistance furnaces to combust samples at >950°C. After a delay oxygen is passed over the sample and carries the CO_2 through dust and water vapour traps and into an infrared detection system (Nelson and Sommers 1996). Soil samples were crushed and sieved to <100 μm. Approximately one gram of soil was combusted in each analysis.

2.2.8 *Carbonate*

We used the acetic acid dissolution method, described by Loeppert and Suarez (1996). Soil samples were crushed and sieved to <100 μm. Sample size varied between 1 to 2 g.

2.2.9 *Organic carbon*

This was calculated as the difference between total carbon and carbonate.

2.3.0 *Moisture content*

All moisture contents were calculated on a dry weight basis with samples dried at 105° C until they exhibited no further change in weight.

2.3.1 *Aggregate size fractions*

We constructed a rotary sieve (Figure 2.1) using as guidelines the work of Lyles et al. (1970). The rotary sieve consists of a set of 5 cylindrical sieves, fitted one inside the other, the largest inside and smallest outside, and a feeder belt. The sieve sizes range from 2 mm to 28 mm in a 4SQRT2 series (2, 4, 8, 16) for the first four (we could not procure 32 mm screen, so we substituted 28 mm for the largest, size fraction), yielding six size fractions of aggregates. The rate of feeder belt movement and rotary sieve rotation are controllable. We operated the rotary sieve at 7 rpm, the speed recommended by Lyles et al. (1970).

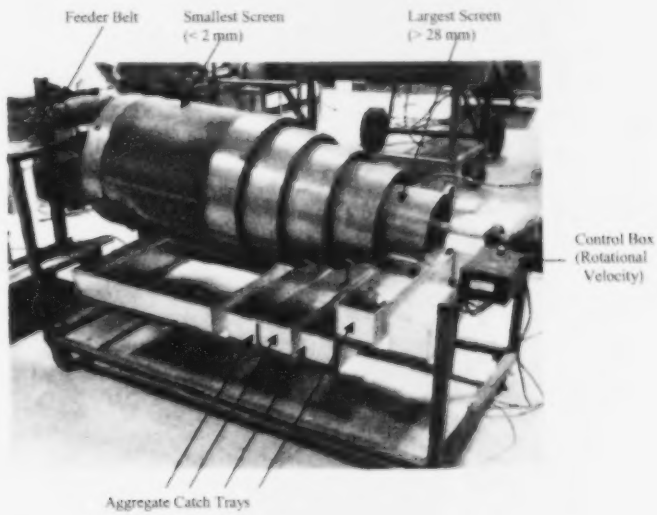

Figure 2.1. Rotary sieve for separating aggregate fractions

Approximately one half of the 450 samples originating from eight sites were processed through the rotary sieve with no pre-treatment except the removal of the oversized

aggregates (those >50 mm diameter that could not fit into the rotary sieve). After sieving the weight of each size fraction was recorded, including the oversize class. The aggregates falling through the 2 mm screen were sieved into five more size fractions (1, 0.5, 0.25, 0.125 and <0.125 mm) using a Gilson sonic sifter. A 75 g sample of the <2 mm aggregates were sieved for 3 min using a combination of sonic vibration and automated tapping. After sieving, the weight of each size class was recorded and used to calculate the fraction of aggregates pertaining to each size class.

The average aggregate size and spread of the distribution were calculated as the geometric mean and geometric standard distribution, using the identical procedure as described above under the topic of *Particle size distribution*, except that aggregate size diameters are measured in millimeters (mm). Soils from different sites and the differences between wellsite and control areas were then compared on the basis of differences between means and standard distributions.

2.2 Results and Discussion

2.2.1 *Particle size distribution*

The average particle size (geometric mean) is smaller on-lease, including samples from around the wellhead, than off-lease for all sites but Hayter 1 (Table 2.1). The mean particle size calculation is based on the analysis of approximately 25 samples on-lease and 25 samples off-lease at each site. Therefore, we know that estimates of the mean are precise and that differences are real. We can deduce that, in all cases but one, well construction and reclamation have led to an increase in clay content in the surface soil horizon. The Chipman site is notable for the increase in fine particles that occurred as a result of well construction. What was originally a relatively medium textured soil became fine textured soil. Other sites showing remarkable changes in particle size as a consequence of oil well development are Ranfurly (albeit this site was coarse textured prior to well development), Vermilion (a special case because the knoll of a moraine landscape was excavated to construct the wellsite), Hythe and Hayter 2. The increase in clay content at all sites could be attributed to: i) the removal of topsoil from the lease and the reclamation of subsoil with higher clay content as the surface horizon, or ii) the

admixing of A and B horizons so that higher clay in the subsoil becomes a major component of the reclaimed land surface. It's also possible that both phenomena have occurred together. Table 2.1 also shows that the average particle size, measured as the geometric mean, differentiates soils from each other in a manner that can be lost when comparing sand, silt and clay percentages.

Table 2.1. Mean particle size (μm) by site and location (off- or on-lease.)

Site	Location	
	Off-lease	On-lease[1]
Ranfurly	105.5	64.7
Hayter 1	43.4	44.2
Chipman	40.9	13.6
Vermilion	34.5	21.5
Olds	14.5	13.1
Rimbey	12.8	11.8
Hythe	10.3	6.7
Hayter 2	9.0	7.2

[1]On-lease is average of wellhead and remaining lease samples.

Further elaboration of the differences in particle size at each site is shown in Table 2.2. All sites except Olds and Hayter 1 show significant differences in average particle size between the control (off-lease) and the lease or wellhead or both. The wellhead soils exhibit the smallest average particle size. This might be explained by their higher degree of disturbance.

Table 2.2. Mean particle size, standard deviation and texture class by site and location within site

Site	Location	Particle size parameters		
		Mean (μm)	St. dev.	Texture class
Rimbey	Off-lease	12.8 a[1]	9.3 a[1]	silt clay loam
	Lease	12.4 a	10.4 ab	silt clay loam
	Wellhead	10.1 b	11.4 b	silty clay
Olds	Off-lease	14.5 a	8.7 a	silt clay loam
	Lease	13.3 a	9.4 b	silt clay loam
	Wellhead	12.5 a	9.5 b	silt clay loam
Hythe	Off-lease	10.3 a	8.6 a	silt clay loam
	Lease	6.8 b	9.2 b	silty clay
	Wellhead	6.6 b	9.2 b	clay
Hayter 1	Off-lease	43.4 a	11.1 a	loam
	Lease	44.8 a	13.0 b	loam
	Wellhead	42.3 a	14.2 b	silt loam
Hayter 2	Off-lease	9.0 a	10.7 a	silty clay
	Lease	7.3 b	11.0 a	clay
	Wellhead	7.0 b	11.2 a	clay
Vermilion	Off-lease	34.5 a	10.4 a	silt loam
	Lease	25.7 a	12.2 b	silt clay loam
	Wellhead	16.0 b	13.7 c	clay loam
Ranfurly	Off-lease	105.5 a	7.7 a	silt loam
	Lease	64.5 b	8.3 a	silt loam
	Wellhead	64.9 b	8.8 a	silt loam
Chipman	Off-lease	40.9 a	9.6 a	silt loam
	Lease	13.9 b	13.1 b	silt clay loam
	Wellhead	12.5 b	13.2 b	clay

[1]Values followed by same letter in the same column and under the same site are not statistically different at 0.05 probability.

The geometric standard deviation reported in Table 2.2 is a measure of the particle size range or "spread". Essentially, this number quantifies the proportion of clay, silt and sand. A sample containing 31% clay, 62% silt and 7% sand would have a geometric mean of 4.5 μm and a geometric standard deviation of 5.2 (Figure 2.2). Other mixtures of clay, silt, and sand exhibit a logical pattern of changing geometric mean and geometric standard deviation (Table 2.3). As one would expect, the geometric mean increases with higher sand content and decreases with higher clay content. On the other hand, the geometric standard deviation is at its lowest when silt content dominates the mixture (Table 2.3: clay 10%, silt 80%, sand 10%) or when two adjacent components contain the entire sample mass (e.g., clay 80%, silt 20%). It should be noted that the lowest geometric standard deviation possible, when referenced against sand, silt and clay fractions[2], is 1.0, representing a sample with 100% in any one of the three fractions. Similarly, the highest possible geometric standard deviation is 32.02, where the sample contains 50% clay and 50% sand.

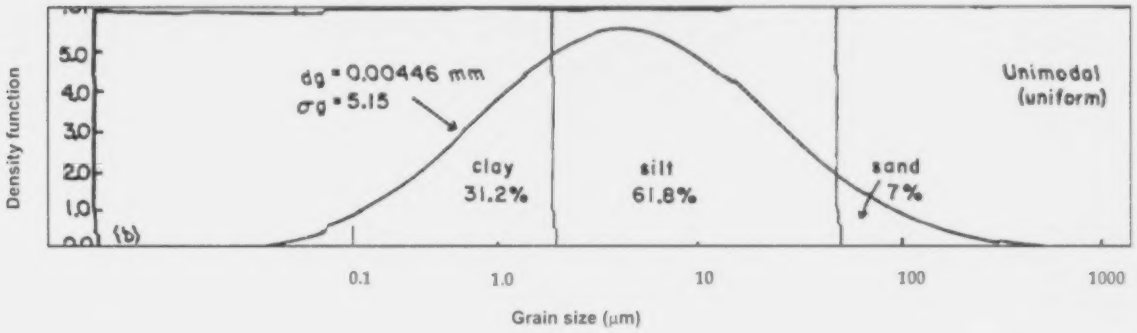

Figure 2.2. A hypothetical example of the relationship of geometric descriptors (μ_x, σ_x) to sample contents of clay, silt, and sand (Shrirazi et al. 1988)

[2] If a particle size distribution was calculated on the basis on multiple fractions, as is the case for samples analyzed in this study, a geometric standard deviation exceeding 32.02 is possible.

Table 2.3. Relationship of geometric mean (μ_x) and geometric standard deviation (σ_x) to percentage clay, silt and sand (adapted from Shirazi and Boersma 1984)

Clay (%)	Silt (%)	Sand (%)	Geometric mean μ_x (μm)	Geometric standard deviation σ_x
0	0	100	1030.0	1.0
10	40	50	118.0	10.5
10	80	10	27.1	4.7
20	20	60	12.3	16.4
20	40	40	58.9	13.7
30	40	30	29.5	14.7
30	60	10	14.1	7.7
50	30	20	10.6	14.7
50	0	50	32.0	32.0
60	30	10	5.3	9.8
60	10	30	11.1	22.5
80	20	0	1.9	3.7
80	0	20	4.0	16.0

The samples from all well leases reported in Table 2.2 have higher geometric standard deviations than corresponding soils in the surrounding areas. This implies a shift from silt to sand or clay size fractions or both, a conclusion that we've already alluded to in the discussion above in reference to changes in geometric mean.

2.2.2 *Organic matter*

With the exception of two sites, the soil organic matter contents decrease significantly as a result of well development (Table 2.4). Although manure was added to soils on each lease[3] and in the case of the Olds site chicken manure was added for 13 consecutive years (Neil Unger, personal communication, September 2001), organic matter levels did not stabilize at the pre-disturbance levels. In the beginning, organic matter levels

[3] There are individual records for each lease in Alberta Environment dating from 1981 to 1983 ordering the addition of manure and other amendments to lease sites.

decreased as a result of topsoil removal; subsoils never have as much organic matter as topsoil. Manure additions can temporarily restore gross organic matter content, but manure is rapidly decomposed, almost always resulting in less than one percent of the dry weight of the manure stabilized as soil humus. Contrary to measurements made by other researchers (Campbell et al. 1986, Dormaar et al. 1988, Chang et al. 1990), not even consecutive additions of manure seem to have added significantly to soil organic matter levels at Olds (Table 2.4). If lease areas are shown to be less productive than their counterpart soils in surrounding areas, the lower organic matter levels could be attributed to less carbon input in the lease area. Perhaps, this is best exemplified by a counter-example. The Vermilion site was planted to brome shortly after well drilling was complete, and the lease was left uncut and undisturbed since. Vermilion is one of the only two sites that have no significant difference in soil organic matter contents on-lease and off-lease (Table 2.4). Even visual inspection attests to the accumulation of organic matter on-lease (Figure 2.3). We might conclude that in the case of Vermilion, organic input on the lease has equaled or exceeded the input off-lease. By logical extension, organic carbon input, probably resulting from less crop productivity, has been less on the leases where surrounding soils have significantly higher soil organic matter contents.

Table 2.4. Soil organic matter contents (%) of three locations at nine sites

	Site							
Location	**Hythe**	**Chipman**	**Ranfurly**	**Vermilion**	**Hayter 1**	**Hayter 2**	**Rimbey**	**Olds**
Off-lease	5.00 a[1]	6.32 a	6.40 a	6.64 a	3.44 a	2.87 a	4.49 a	4.18 a
Lease	4.19 ab	2.67 b	4.47 a	6.14 a	2.60 b	2.08 ab	3.2 b	1.43 b
Wellhead	3.71 b	1.83 b	4.27 a	4.88 a	2.16 b	0.72 b	2.78 b	1.27 b

[1]Values followed by the same letter in each column are not significantly different at 0.95 probability.

Figure 2.3. Topsoil slice from lease at Vermilion site

2.2.3 *Carbonate*

The soils of central Alberta, from west to east, are rich in carbonate (Table 2.5). Topsoil pertaining to undisturbed areas around the oil well leases on average has 0.5% as a minimum, and as much as 4% in the off-lease soil at the Chipman site. However, without exception, control soils have less carbonate than lease or wellhead soils. The reason for this is probably that subsoil carbonates were admixed into the surface soils during well construction. Carbonate content is a good candidate for a simple field test to estimate the degree of admixing on a wellsite; carbonate is easily estimated in the field using the effervescence test (Schoeneberger et al. 1998). Special note should be made of carbonate levels at the Olds site. The off-lease values were high (2.8%) while on-lease and wellsite values were higher (3.5% and 4% respectively). However, these values are probably not the result of admixing, as attested to by the lack of change in geometric mean particle size when comparing on- and off-lease values. Instead, carbonate levels at Olds can be attributed to the effect of continually applying chicken manure to the lease and surrounding area.

Table 2.5. Soil carbonate contents (%) of three locations at nine sites

	Site							
Location	Hythe	Chipman	Ranfurly	Vermilion	Hayter 1	Hayter 2	Rimbey	Olds
Off-lease	0.73 a[1]	1.44 a	1.23 a	0.91 a	1.07 a	1.27 a	0.78 a	2.86 a
Lease	1.26 b	2.45 b	1.33 a	1.25 b	1.39 b	1.64 ab	0.91 a	3.89 b
Wellhead	1.03 b	2.41 b	0.90 b	1.73 c	1.88 b	2.24 b	0.93 a	3.98 b

[1]Values followed by the same letter in each column are not significantly different at 0.05 level of significance.

2.2.4 *Bulk density*

We measured bulk density using the 'clod' or large aggregate method. This measurement technique tends to yield slightly higher bulk density values (by about 0.05 g cm^{-3}) than coring techniques because the pores between clods are not included in the total measurement. It should be noted that although the clod method yields values biased towards higher bulk density, the values are always biased in the same direction, and thus the clod method maintains its worth for comparing one soil to another, or treatment against treatment. The advantages of the clod method for measuring bulk density are: i) the soil is not compressed during sample collection, and ii) one person can measure a hundred bulk density samples in the laboratory in one day, thus facilitating intensive sampling and precise results even under conditions of extreme variability. All other methods of bulk density measurement, including the core method, cause sample distortion during sampling or are tedious and slow.

All samples (>400) were measured for bulk density. Six of eight sites have higher average bulk densities in the surface soil on the wellsite than those on the surrounding farmland (Table 2.6). The only exceptions are Ranfurly and Hayter 1, which also have the largest average particle size (geometric means equal to 105 μm and 43 μm, repectively for off-lease soils). It is well known that sandy, or coarse-textured soils are naturally higher in bulk density and undergo less increase in bulk density under

consolidation stresses (Mitchell 1993). The Ranfurly and Hayter 1 sites exhibit both tendencies when compared to other sites in our data set.

Table 2.6. Mean bulk density values (g cm^{-3}) by site and location

Site	Location		
	Off-lease	Lease	Wellhead
Rimbey	1.44 a[1]	1.55 b	1.77 c
Olds	1.26 a	1.39 b	1.36 b
Hythe	1.26 a	1.32 b	1.40 c
Hayter 1	1.54 a	1.58 a	1.60 a
Hayter 2	1.43 a	1.55 b	1.63 b
Vermilion	1.34 a	1.48 a	1.69 b
Ranfurly	1.52 a	1.50 a	1.58 a
Chipman	1.46 a	1.65 b	1.68 b

[1]Values followed by same letter in the same row are not statistically different at 0.05 level of significance.

The lease and wellhead soils at the Hythe, Chipman, Hayter 2, Rimbey, and Vermilion sites show extreme differences in bulk density (0.15 g to 0.30 g cm^{-3}) between wellsite and surrounding farmland (Table 2.6). The surface soils on these leases are much higher in bulk density than those in the control areas. With the exception of Vermilion, the same leases also have the smallest geometric mean particle size. We can deduce that a reduction in average particle size is associated with larger differences in bulk density between control and lease area and wellhead. Soils with significant amounts of clay or fine silt are known to have higher 'packing' ratios than comparable soils with less clay (Marshall et al. 1996). Apparently, clay particles occupy void spaces between silt and sand grains and consequently become denser or more tightly packed. The increase in bulk density from control soil to wellsite might be the result of having admixed clay from the subsoil and having subjected the lease soils to mechanical disturbance that led to a rearrangement of soil particles in less volume.

The soils on the Olds wellsite are significantly higher in average bulk density than those in the associated control areas, but difference is <0.15 g cm^{-3}). There is no significant difference in particle size between control area and lease or wellsite at Olds, hence the change in bulk density may be attributed to the effects of disturbance and consolidation and not to admixing.

The average bulk density of sample points surrounding the wellhead is frequently, but not invariably, higher than the average of remainder of locations within the wellsite boundaries (Table 2.6).

2.2.5 *Aggregate size*

Aggregate size was measured on more than half of the 400 samples. Aggregate size was measured on approximately 10 off-lease samples per site and 17 on-lease samples per site. Table 2.7 arranges the sites in ascending order of aggregate size on the lease. It should be noted that this order is approximately the inverse order of particle size with two exceptions. In general, average aggregate size is inversely related to average particle size. The exceptions are the Vermilion and Chipman sites. Their average aggregate size is large (20 and 28 mm diameter, respectively), while their average particle size is also large by comparison to other sites. The anomaly in the relationship of aggregate size to particle size can be attributed to the long-term crop cover at these sites. Vermilion has been in a brome grass cover for decades and Chipman has been in pasture. Permanent forage crops produce more roots that are conducive to the formation of larger aggregates than annual crops (Degens 1997).

Table 2.7. Geometric mean aggregate size[1] (mm) and standard deviation[1] of size distribution by site and location

Site	Location			
	On-lease		Off-lease	
	Geometric mean (mm)	Standard deviation	Geometric mean (mm)	Standard deviation
Hayter[1]	2.5	10.0	2.5	10.3
Ranfurly	3.9	14.3	2.3	12.8
Olds	4.4	12.5	3.6	14.1
Hayter[2]	8.5	7.4	6.0	8.3
Rimbey	11.1	7.0	13.8	7.9
Hythe	16.2	6.3	22.8	5.9
Vermilion[2]	19.8	5.9	10.8	10.8
Chipman	27.9	4.0	29.6	4.5

[1]Calculation of geometric mean and geometric standard deviation explained in text under particle size measurements.

[2]Only significant difference in mean aggregate size comparing off- and on-site values.

There is an approximate relationship between aggregate size on-lease and aggregate size off-lease (Table 2.7). In fact, there are no significant differences between on-lease and off-lease aggregate sizes, except at the Vermilion site. In this case, aggregate size off-lease is much smaller than on-lease because the vegetation cover is different. As mentioned, the lease is seeded to brome; the off-lease area is treed, the dominant species is poplar (*Populus tremuloides*). Trees, shrubs, and groundcover do not produce nearly the root biomass of a permanent pasture grass, and thus do not lead to the formation of large soil aggregates in the surface horizons.

The spread of the aggregate size distribution, as measured by the geometric standard deviation, is inversely related to aggregate size (Table 2.7). The larger the mean aggregate size, the narrower the spread of the aggregate size distribution. Consequently, soils that have large aggregate-size means, such as the soils at Chipman and Vermilion planted to permanent forage crops, have most of their aggregates in a small group of size classes. Very little of the aggregate mass is contained in the small size groups. Conversely, soils having on average small aggregates, such as silty or sandy soils at the Ranfurly or Hayter 1 sites, planted to annual crops, have a wide

distribution of aggregate sizes; they have a large portion of their mass in small size classes and a significant portion in larger fractions as well.

3. PHASE 3. TILLAGE RESISTANCE AND VEGETATION RESPONSE

3.1 Introduction

We have shown in Phases 1 and 2 of this project that some reclaimed wellsites have significantly different structures in the surface horizon than those in nearby off-lease soils. The largest structural difference was measured as an increase in bulk density. There were also significant differences in some cases in average particle size (geometric mean), the distribution of particle size (geometric standard deviation), organic matter content and the concentration of soil carbonate. These latter properties were used to explain or account for the differences in bulk density.

Under agriculture, a change in soil structure is especially important if it necessitates a change in soil management practices or leads to a decrease in plant productivity. Critical soil management practices include: i) required changes in the timing of operations, such as tillage (cultivation), seeding, spraying, or harvest, and ii) any increase in power requirements. Changes in timing due to changes in structure are difficult to measure and subject to vast year-to-year variability. The latter characteristic means that consecutive years' data would be required to evaluate the effect of structural change on the timing of operations. Power requirements, on the other hand, are relatively simple to measure and vary only as a function of the soil and its water content.

Jones et al. (1987) developed an inexpensive, dynamic measure of power requirements using a modified chisel plow, a hydraulic system coupled to a pressure transducer, and a voltage integrator timing device. However, advances in electronics and the widespread ownership and use of all-terrain vehicles, since 1987, encouraged us to think that even simpler, less expensive, and more accurate machines might be developed. Pushing us in the same direction was the observation by many landowners that their power requirements (tractor pulling force) increased when cultivating former wellsites. An "electronic tiller" (E-tiller) could quantify power requirements to compare soil behavior on wellsite and off-lease areas. In addition, the continuous measurement of one physical property (draft) might allow better soil

characterization of other correlated properties, such as particle size or organic matter, while reducing sampling intensity (van Bergeijk et al. 2001).

The objectives of Phase 3 were: (i) to develop an E-tiller capable of measuring tillage resistance in soil at several depths; (ii) to measure and compare tillage resistance of soils on wellsites and surrounding lands in the agricultural areas of Alberta; and (iii) to compare vegetation productivity on wellsites and surrounding lands and assess the role of changed physical properties in determining modifications in crop production.

3.2 Materials and Methods

3.2.1 *Electronic tiller*

We designed and constructed a portable machine that measures the force required to pull a cultivator through soil. The E-tiller easily connects to an ATV (all terrain vehicle) and is completely powered by the ATV's power supply (Figure 3.1). There are two types of shovels or blades currently in use on the E-tiller. The standard "V" shovel comes with a spring shank and up to seven of these shovels can be mounted on the tiller (Figure 3.2). The spacing and configuration of the shovels is adjustable, with allowance for shovels to be mounted before or after the tiller wheels, and from 6" to 48" apart. The depth the shovels enter into the soil can be varied from 0 to 6" and is electronically adjusted. The tiller can also be fitted with subsoil ripper blades. These blades can be electronically adjusted to a maximum depth of 10". The electronic tiller itself is a modified version of the commercially available Quadivator (www.quadivator.com). The modifications include: the mounting of a load cell in the Quadivator drawbar hitch and the mounting of a speed sensor on one of the Quadivator wheels (Figure 3.2). Our electronic tiller is customized with a control panel that houses a depth control switch, data loggers, and monitors of force and speed (Figure 3.3). LED meters provide the operator with continuous readings for drawbar force and travel speed. Data loggers provide a continuous record of these parameters. The data loggers are easily disconnected from the tiller's electronic control panel and downloaded to a laptop or PC. The data loggers include software that allows data analysis in tabular or graphic form.

Figure 3.1. E-tiller pulled by a quad

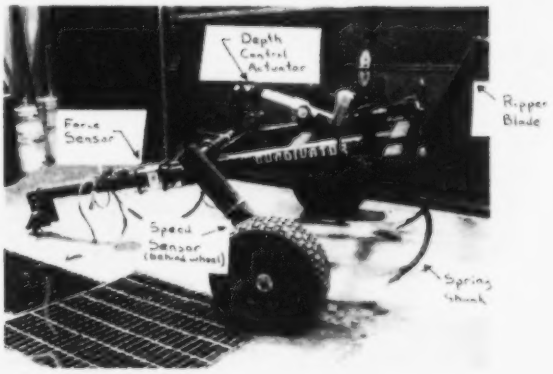

Figure 3.2. Close-up of the E-tiller showing sensors, depth actuator and cultivator shovel options

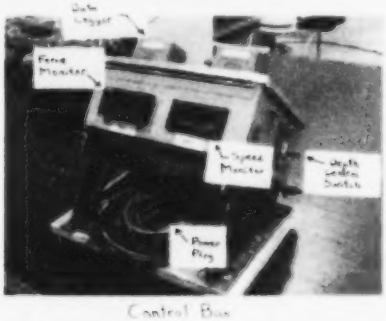

Figure 3.3. Control box and visual display

3.2.2 *E-tiller field trials*

Comparative tillage resistance measurements were made on two successive years (2001 - 2002) at five of the eight sites studied in Phase 2:

- Ranfurly
- Hayter 1
- Hayter 2
- Rimbey
- Olds

In 2001, we made four passes within the boundaries of each wellsite lease and four passes outside the lease boundary. We mounted two V-shovels on spring-arms and set the depth at 4" for each run. Passes done within the lease were located 5 m on either side of the wellhead. Passes conducted off-lease were parallel to the outside boundary and 10 m outside the lease boundary. The E-tiller was pulled by a quad (Honda Foreman 400).

In 2002, we conducted field trials for tillage resistance on the same five sites. Unlike the trial runs of the previous year, in 2002 only four passes were made at each site, except at Ranfurly where irregularities in lease boundaries restricted us to two passes. The passes began 100 m outside the lease boundary, crossed the lease within 1 m of the wellhead, and crossed the opposite boundary by 100 m before terminating. Consequently, each pass incorporated a continuous record of changes in draft (force measured as pounds) outside and inside the lease. Two passes were made with the blade set at 4" depth, and two passes were made with the blade set at 8" depth. In 2002 we used a tractor to pull the E-tiller to allow us to measure tillage resistance at 8" and to even out pulling speed (43 rpm or 0.82 m s^{-1}).

3.2.3 *Crop productivity*

In 2002 we collected crop samples on- and off-the wellsites and compared productivity. Annual crops were sampled when they were deemed mature and still standing, with the exception of Olds where the canola crop was swathed first, allowed to ripen, then a section of the swatch was sampled. The only pastureland site sampled was Chipman

and this site was sampled around the same time as the annual crops. At each site, after the wellhead was marked, meter square sections were sampled around the wellhead, then in concentric patterns at predetermined distances from the wellhead until the lease boundary was reached. Outside the lease boundary, meter square sections were marked out at equal distances around the entire lease. No samples were taken where surrounding soils merged into swamp or bush.

The vegetation inside each meter square was cut with grass shears and placed in cotton bags marked with the site and sample number. The bags were transported to ARC and hung outside to air-dry for approximately one week. The drying process was completed by placing the bags in a dryer set at 30°C for 3 days. Then the plant bags were weighed, samples were thrashed in a tabletop thresher, and the grain or oilseeds were cleaned with a blower and weighed. Any sticks, dirt or other non-plant material were removed from the bag before any weights were taken. One-hundred seed weight was measured by standard seed analysis technique (International Seed Testing Association 1976). The pastureland samples consisted mostly grass and did not require thrashing.

3.3 Results and Discussion

3.3.1 *Measuring soil resistance by power and force*

As shown in Figure 3.4, when the E-tiller was pulled by a quad, the speed varied between 60 and 75 rpm (1.14 to 1.42 m s^{-1}). The change in speed raises the question of which variable best represents soil resistance to tillage: force or power? Power is a function of force and velocity:

$$\text{Power} = \text{Force} \times \text{Velocity}$$

Expressing results in terms of power thus has the disadvantage of varying with changes in velocity. As the tiller is pulled through soil, consistent results would result only if velocity were kept constant. And under these conditions, force (which can be measured directly) would be the same as power. Furthermore, we found that tiller draft force remained constant even when speeds varied from 60 to 130 rpm (Figure 3.5). Thus, force is the better measure of soil

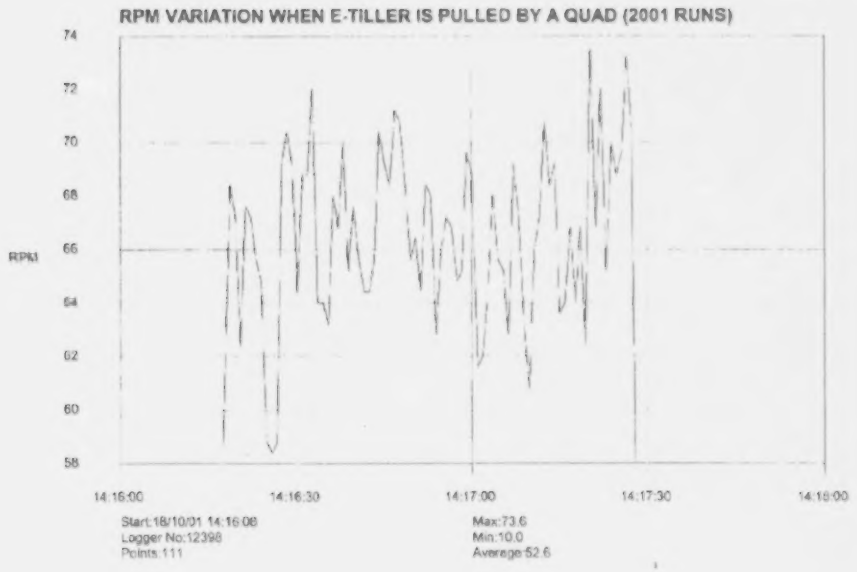

Figure 3.4. Variation in rpm when E-tiller is pulled by a quad

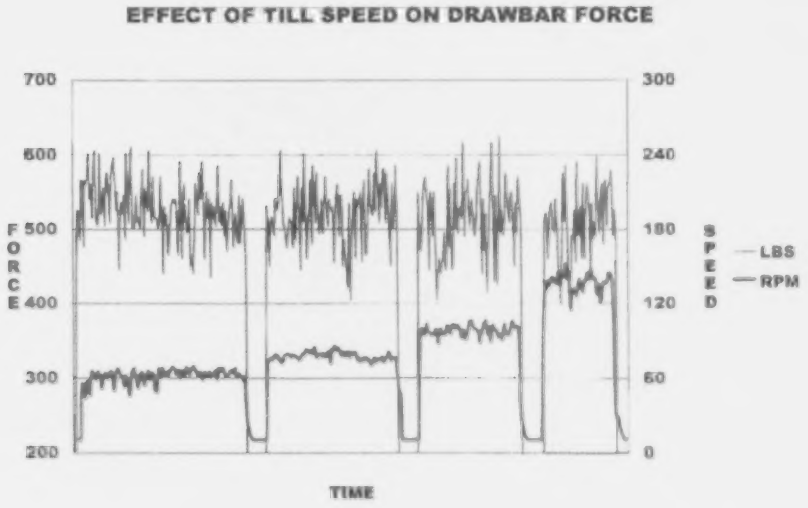

Figure 3.5. Effect of speed (rpm) on measured drawbar force (lbs)

resistance to tillage because it is less variable than calculated power requirements and yet is a sensitive, quantitative measure of soil resistance.

3.3.2 *E-tiller measurements of force—Year 2001*

An example of the summary of the 2001 measurements of draft force on- and off-lease is shown in Figures 3.6. In this year, the E-tiller was fitted with two V-shovels that were pulled with a quad at approximately a 4" depth. The summary of other sites measured by the E-tiller in 2001 are in the Appendix. Figure 3.7 provides the actual draft force values in relation to pass on which the summary (Figure 3.6) is based. It should be noted that runs 1 to 4 correspond to on-lease measurements, while runs 5 to 8 correspond to off-lease measurements.

With maybe the exception of Ranfurly site, there are no obvious differences in average draft forces between off-lease and on-lease passes. The Ranfurly site may show slightly higher draft force on-lease than those averaged off-lease. Since the Ranfurly lease did not show significant difference in bulk density between off- and on-lease averages (Table 2.6), it is unlikely that any perceived differences in draft force are meaningful. Given that on sites, such as Hayter 2, Rimbey and Olds, where there were significant difference in bulk density off- and on-lease and little differences in draft force, we conclude that tillage resistance at 4" depth is not sufficiently sensitive to indicate a change in this soil management property.

Ranfurly

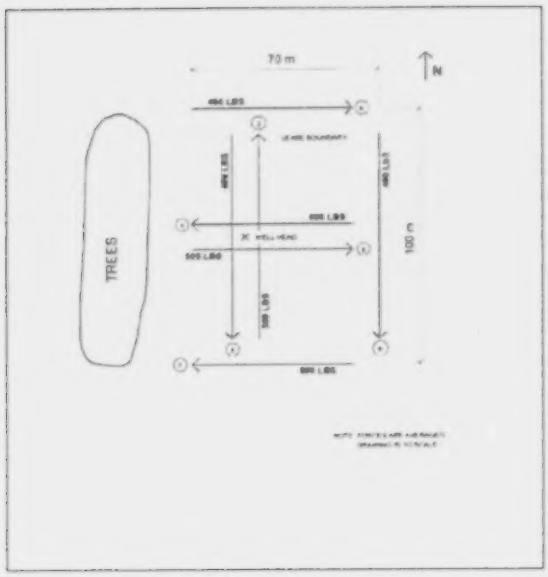

Figure 3.6. Summary of draft forces at Ranfurly site on- and off-lease

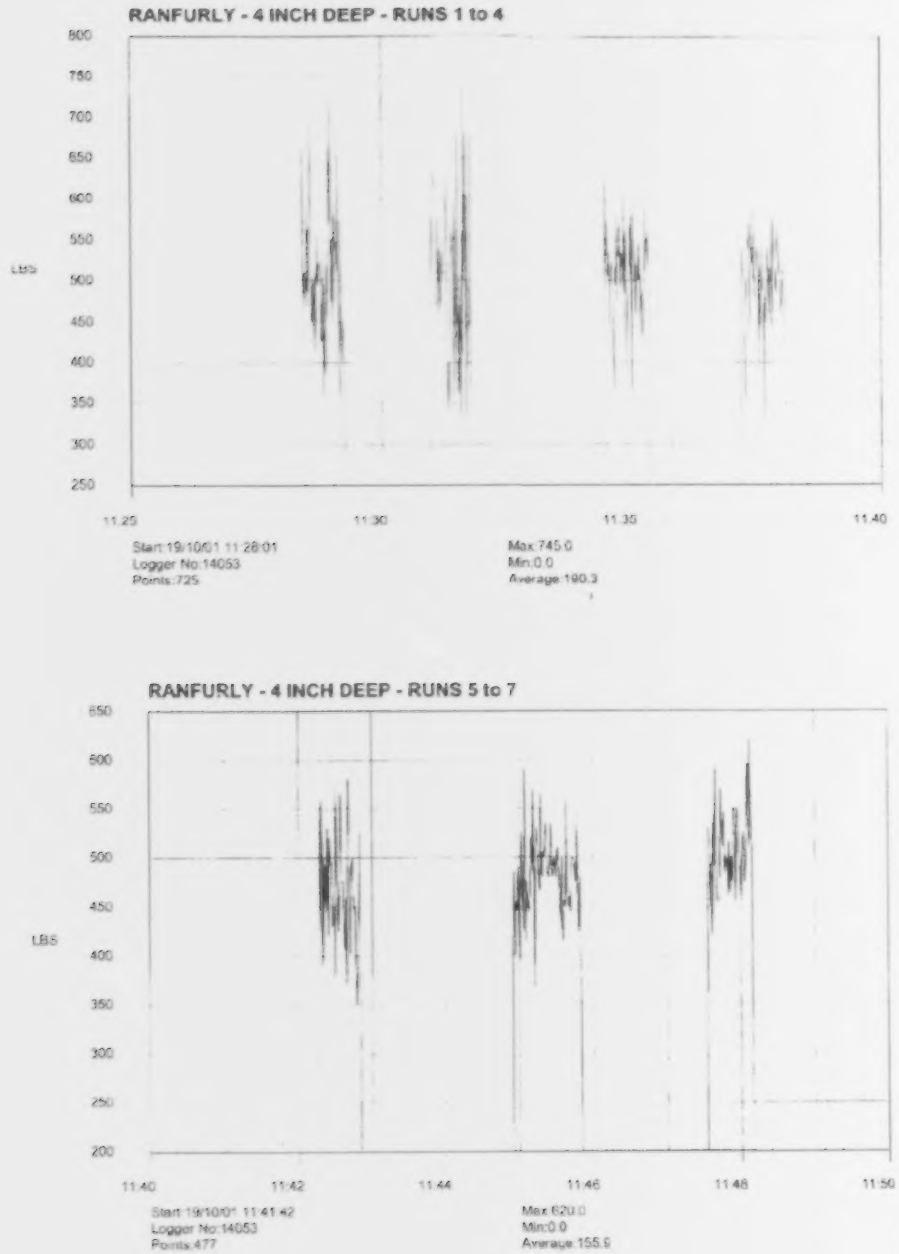

Figure 3.7. Actual record of draft forces (lbs) by site and pass (1-4 are on-lease; 5-8 are off-lease)

3.3.3 *E-tiller measurements of force – Year 2002*

In this year, the E-tiller was fitted with a single ripper blade, the E-tiller was pulled by a tractor at approximately 43 rpm (0.82 m s^{-1}), and passes were made at the 4" and 8" depths. Due to the larger machine (tractor), velocity was near constant (Figure 3.8) when compared to the quad-drawn E-tiller. The layout of the E-tiller passes on each site was considerably different in 2002 (Figure 3.9) when compared to that of 2001. It should be noted that each pass starts from outside the lease boundary (100 m), crosses the lease, and terminates 100 m beyond the lease boundary on the opposite size.

Force measurements from the E-tiller at 4" depth fitted with a single ripper blade are shown in Figure 3.10. Because of the way the E-tiller passes are made, if a change in bulk density on the lease causes forces to increase, we should see the change in the midsection of each lease. Rimbey and Olds sites, both demonstrated to have significantly higher bulk density values on-lease than off-lease, show slight increase in forces at the midpoint of the pass (Figure 3.10). In contrast, the Hayter 1 site does not show a noticeable change in force when comparing off-lease to on-lease data, and neither did this site have a significant difference in bulk density. There were operational problems with the E-tiller at other sites, such as broken ripper blades, that prevented data analysis. In summary, the E-tiller fitted with a ripper blade and pulled at nearly constant speed by a tractor is seemingly capable of denoting relatively small differences in soil resistance that exist in topsoil, but these would need to be confirmed by intensive sampling for properties such as bulk density.

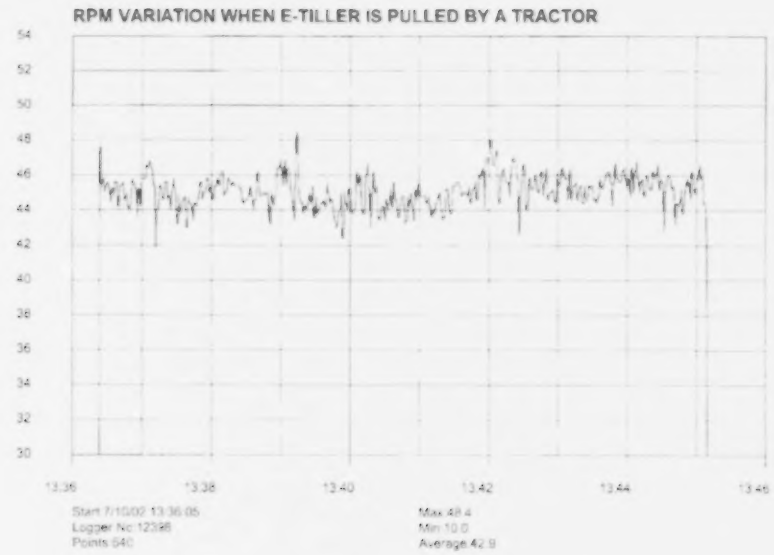

Figure 3.8. Variation in velocity (rpm) of E-tiller when pulled by tractor

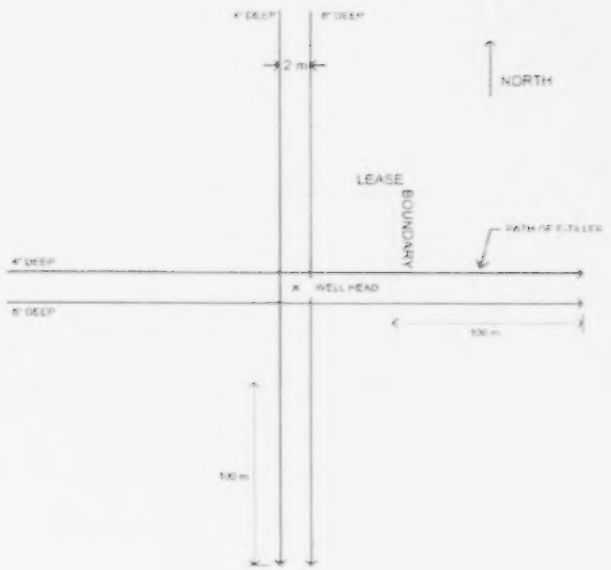

Figure 3. 9. General layout of 2002 E-tiller passes

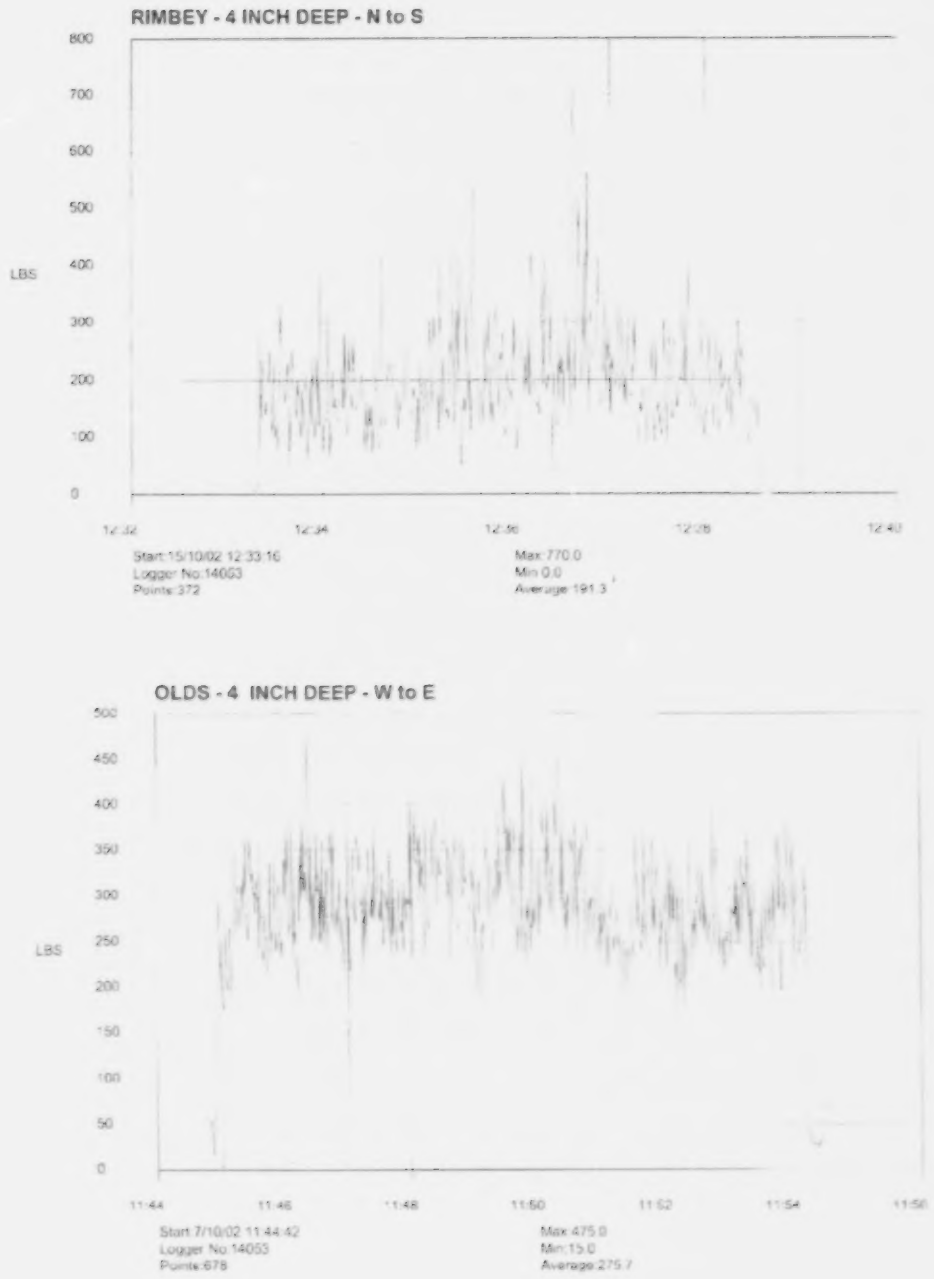

Figure 3.10. Draft force (lbs) at 4″ depth on transect from control area to wellhead to control area

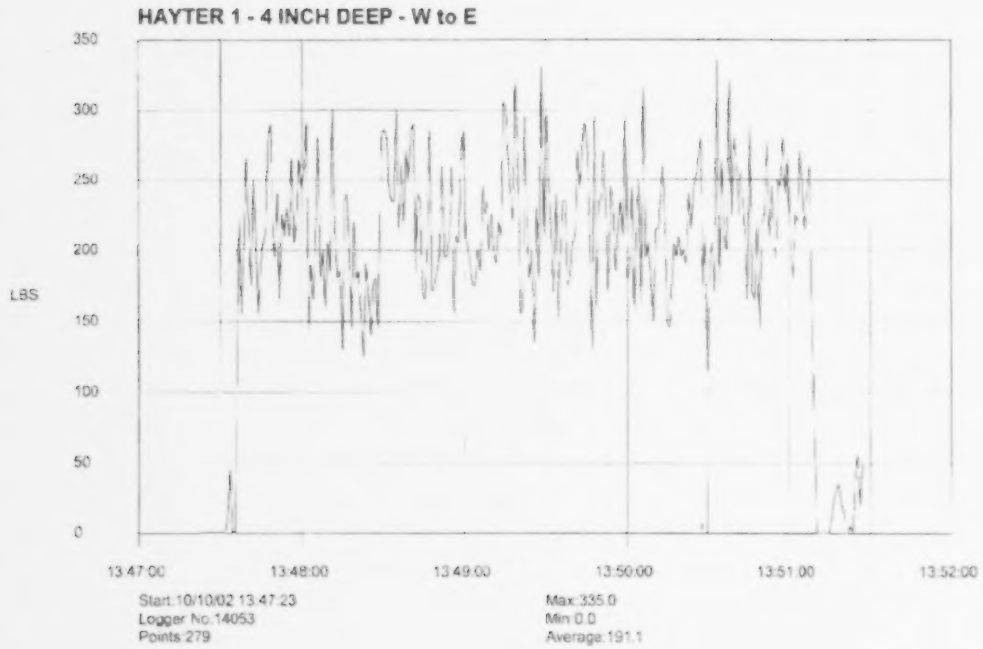

Figure 3.10. Draft force (lbs) at 4″ depth on transect from control area to wellhead to control area

The E-tiller measurements of force at an 8″ depth underline the substantial differences in soil resistance between lease area and the surrounding soil (Figure 3.11). All sites that were studied showed similar differences at 8″ depth between lease and surrounding soil; we show data from the Rimbey and Olds sites only. This project did not measure other subsoil properties, such as bulk density, but on the basis of differences in draft forces, the subsoils on the weilsite leases are severely compacted. The E-tiller is demonstrably useful in delineating large contrasts in bulk density. It could be used to select out nearly any size of area of compacted soils, but the smaller areas would need intensive sampling by means of small distances between transects.

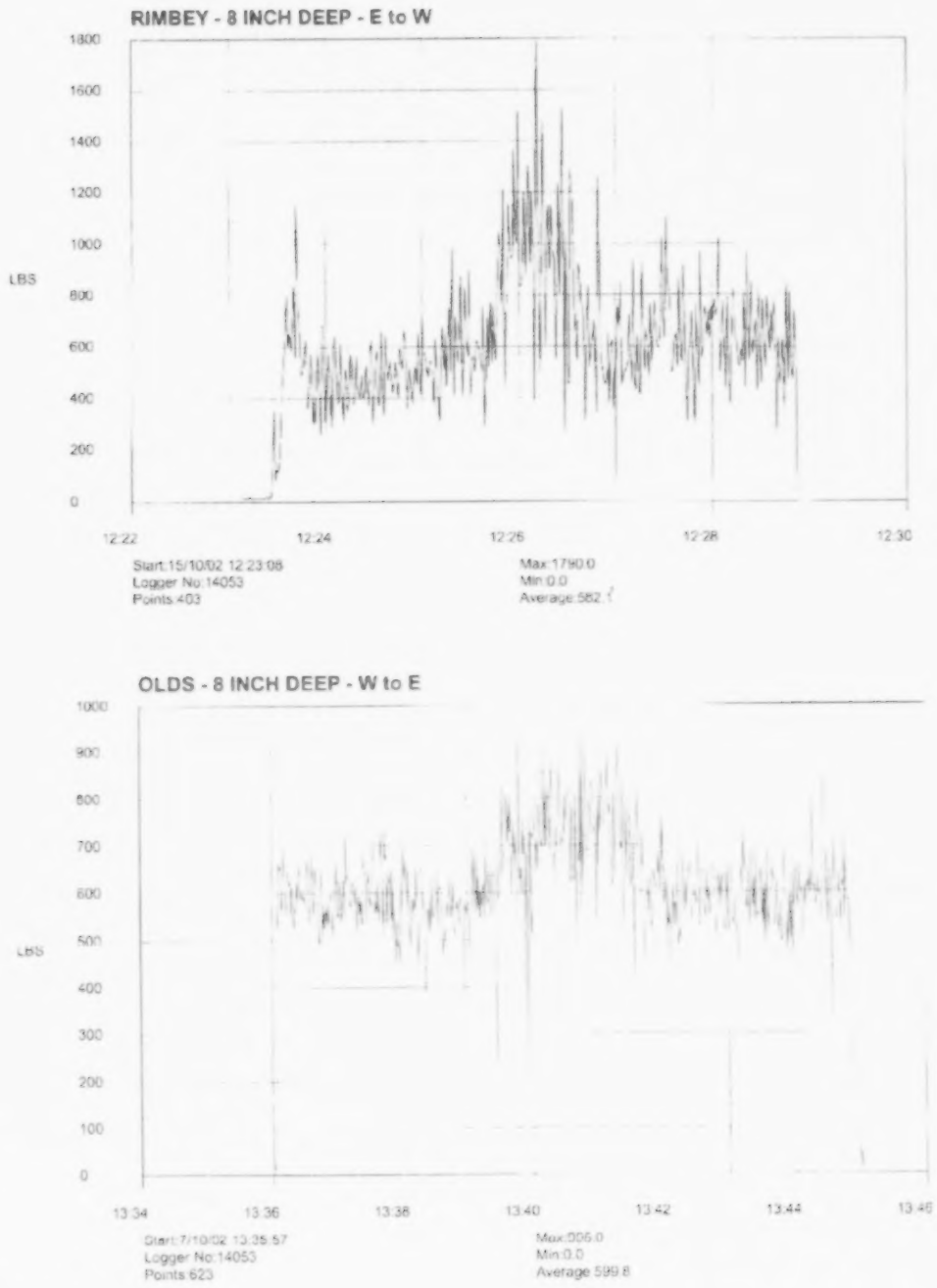

Figure 3.11. Draft force (lbs) at 8″ depth on transect from control area to wellhead to control area

3.3.4 *Crop measurements*

The year 2002 was extremely dry across the central and northern parts of Alberta. Crop yields at all sites were severely depressed due to poor conditions for germination and worsening conditions for crop growth. However, Rimbey and Olds sites, seeded to barley and canola, respectively, showed a significant difference in total biomass yield between off-lease and lease areas (Table 3.1). The off-lease productivity was higher than that on the lease or around the wellhead. Grain yields and one-hundred seed weight lots were not significantly different at either site. Pasture yields off-site at the Chipman site were also significantly higher than pasture yields within the lease area (Table 3.2), but all pasture yields were depressed. Total biomass yield from wheat was not significantly different at either Hayter site. In fact, crop performance at both Hayter sites was so depressed that the operators harvested wheat crops for their small silage or hay value, as opposed to waiting for extremely small grain yields.

By chance, we tested crop productivity during one of the driest Alberta summers in several decades. Unfortunately, this meant that yields and biomass production was minimal. However, the measured changes in soil structure on-lease at Rimbey, Olds and Chipman translated into lower biomass production when compared to surrounding areas. In order to confidently predict that the differences in crop productivity could be attributed to the changes measured in soil properties, we would need several years of measurements when moisture levels were less limiting.

Table 3.1. Vegetation results at Rimbey and Olds sites

Unit of measure	Rimbey (barley)			Olds (canola)		
	Off lease	Lease	Wellhead	Off lease	Lease	Wellhead
Biomass (t ha^{-1})	5.43 a	4.74 b	4.33 b	31.88 a	25.24 b	23.56 b
Grain yield (t ha^{-1})	3.03 a	2.83 a	2.64 a	8.30 a	6.54 a	6.31 a
100 Seed wt (g)	4.01 a	3.86 a	3.86 a	0.51 a	0.53 a	0.54 a

[1]Values in same row under same site followed by same letter are not significant at 0.95 level of significance.

Table 3.2. Total biomass (t ha^{-1}) on three sites

Site		Off-lease	Lease	Wellhead
Chipman	pasture	1.6 a[1]	0.9 b	0.7 b
Hayter 1	wheat	1.2 a	1.3 a	0.7 a
Hayter 2	wheat	1.4 a	1.6 a	1.4 a

[1]Values in rows followed by same letter are not significant at 0.95 level of significance.

4. DISCUSSION

The goal of this project was to answer three questions or groups of questions:

1. Over long periods of time do surface soils on wellsites where topsoil has not been replaced develop structure similar to nearby control areas, and how are the underlying soil properties related to the state of structural development?
2. What is an acceptable measure of soil structure on wellsites and control areas to make quantitative estimates of differences?
3. What is the relationship between soil structure properties, soil management requirements, and plant productivity?

In order to deal with the first question, we had to answer the second: what measurement could we use to compare soil structural states of wellsite and control areas? For our purposes, the best measure of structure is bulk density. The reasons for this choice based on results reported in this study and others are:

- The lowest coefficient of variation (10%) of all properties related to soil structure (Naeth et al. 1991).
- Standardized procedure for normalizing the effects of water content.
- A wide range of measurement techniques to fit almost any situation.
- Availability of inexpensive measurement techniques in the field and laboratory.
- Direct association to and related calculation of porosity
- Historical and current research relating bulk density to other soil properties important in soil structure, to plant response, and to soil management options.
- Widespread and intuitive understanding of values and differences in relation to practical land management issues

Although bulk density is among the least variable of soil physical properties, as attested to by the very low coefficient of variation, many replications are needed to detect small differences. During the first phase we replicated bulk density measurements three times

and were not able to separate what appeared to be substantially different structures. In the second, phase nine reps were usually sufficient to characterize changes in bulk density around the wellhead, but much more precise separation of effects were achieved by the 15 to 25 replications of the lease and control areas. Bulk density measurements met statistical requirements for precision.

Bulk density is one of the few measurements of soil structure that is based on a standardized procedure for normalizing the effects of water content. Bulk density-water content relationships can be standardized by measuring bulk density after air-drying or oven-drying, both points representing residual shrinkage or very small changes in volume upon further drying (McGarry and Malfant 1987). We measured bulk density after air-drying the clods; therefore, our bulk density values reflect the minimum porosity under natural conditions. However, every sample was processed the same, providing for valid comparisons across soils and locations. Had we measured the shrinkage curve—the change in volume (porosity) in relation to change in water content—we could have provided more pertinent information on soil structure, such as the maximum porosity, saturation water content, or minimum bulk density (all terms refer to the same point on the shrinkage curve), air-entry point, total shrinkage, and the shrinkage between any two water contents. Unfortunately, full shrinkage measurements are expensive, and there's no reason to believe that less samples would be needed than for precisely estimating dry bulk density[4]. In most applications, bulk density is measured without drying to standard matrix water potentials, nor is shrinkage measured or estimated. But even under these uncontrolled conditions, when bulk density is measured at ambient water content, one still measures water content, thereby allowing the effect of water content to be taken into account.

We used the core method for measuring bulk density in the field and the clod method in the laboratory. In addition to these there are excavation and radiation methods. There is no one correct way of measuring bulk density; the variety of available approaches allows one to choose according to the nature of the soils under investigation, the ease of

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[4] We did not find any estimates of the coefficient of variation of any component of soil shrinkage.

collecting or analyzing samples in the field, the required precision, and the budget for analysis.

The exact physical relationship of bulk density to porosity, incorporating a measurement or assumption of particle density, connects bulk density to a wide variety of other important characteristics of soil structure and plant response: aeration, water holding capacity, hydraulic conductivity, and thermal conductivity. There is no other soil measurement so intimately related to all aspects of porosity and the features it determines.

Bulk density is also the most commonly used variable for relating research in soil structure and plant response. The advances required are to refine our understanding of its multiple interactions with other soil properties, such as soil strength, and the way plants respond to small changes in bulk density. This is discussed below in more detail under the topic of 'non-limiting water range'.

We attempted a second quantitative measure of soil structure by dry sieving but the results were more variable than bulk density. In our attempt to reduce measurement error of aggregate size, we standardized sample pre-handling and measurement procedures. A special rotary sieve was constructed for large (> 2 mm) aggregates, and small aggregates were sieved into five fractions using a sonic sieve apparatus that imparted as little energy as possible. Even with these precautions, estimates of the geometric mean aggregate diameter were too imprecise to separate differences between lease and surrounding soil.

With our decision to focus on bulk density, we are in a position to address the question as to whether surface soils on wellsites where topsoil has not been replaced develop structure similar to nearby control areas over long periods of time. For the most part the answer is: No. *Soil structures on wellsites that have had their topsoil removed are significantly different than their counterparts on control soils, even after 30 years.* Six of eight sites that we studied had significantly different surface soil structure, measured as higher average

bulk density values, on the lease than those of the control soils off the lease. On five of those six leases, the difference in bulk density between wellsite and control was large enough (0.15 to 0.30 g cm^{-3}) to suggest that plant productivity would be reduced. Our reasoning is as follows:

- Bulk density affects the relationship between 1) water and mechanical impedance, and 2) water and aeration. The two relationships with water are opposite: decreasing water content increases mechanical resistance which in undesirable, but increases aeration which is desirable, and *vice versa*.
- An increase in bulk density intensifies the effect of water on both of these parameters (Letey 1985).
- Under dry conditions increased bulk density limits plant growth by increasing mechanical impedance to plant roots (Taylor 1971) and decreasing available water supply (Archer and Smith 1972).
- Under wet conditions increased bulk density limits plant growth by reducing air filled pore space, leading to an oxygen deficiency or CO_2 excess (Glinski and Stepniewski 1985).

These limitations have been combined into a single parameter called the "non-limiting water range", NLWR (Letey 1985), or "least limiting water range" (da Silva et al. 1994). Inside the NLWR, plant growth not limited; outside the NLWR, plant growth is most limited. As bulk density increases and soil structure decreases, the NLWR narrows dramatically as shown by moving from A →B →C in Figure 4.1. The uppermost figure (A) represents soil at a low bulk density level; the middle figure (B) represents the same soil with slightly increased bulk density; and the bottom figure (C) represents the same soil at a high bulk density level. Progressing from A to C, the non-limiting water range decreases to a fraction of the original range. On both the drier and wetter sides of the NLWR, plant growth will be negatively affected. Therefore, as a result of an increase in bulk density, the range of soil water content at which plant growth is limited is expanded.

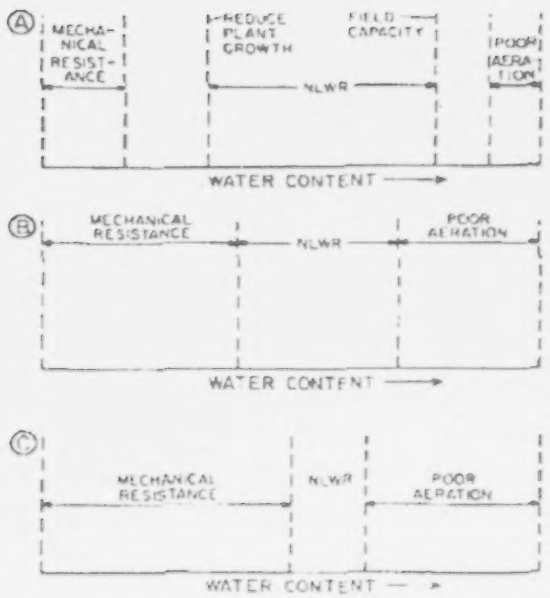

Figure 4.1. Generalized relationship between soil water content and restricting factors for plant growth for soils with increasing bulk density and decreasing structure in going from case A to C (Letey 1985)

Figure 4.2 shows actual measurements of water content and bulk density of a silt loam soil at four critical levels of water content that define the limitations due to water supply (field capacity and permanent wilting point), air-filled porosity, and soil resistance (da Silva et al. 1994). The shaded area in both figures represents the least limiting water range (LLWR). In this soil, no matter what the water content, bulk density values exceeding 1.52 g cm^{-3} restrict plant growth (i.e, they are outside the zone of least limiting water range). The cause of the restriction is lack of air-filled porosity if water content is more than ~32% (v/v) and excessive soil resistance if water content is less than 32%.

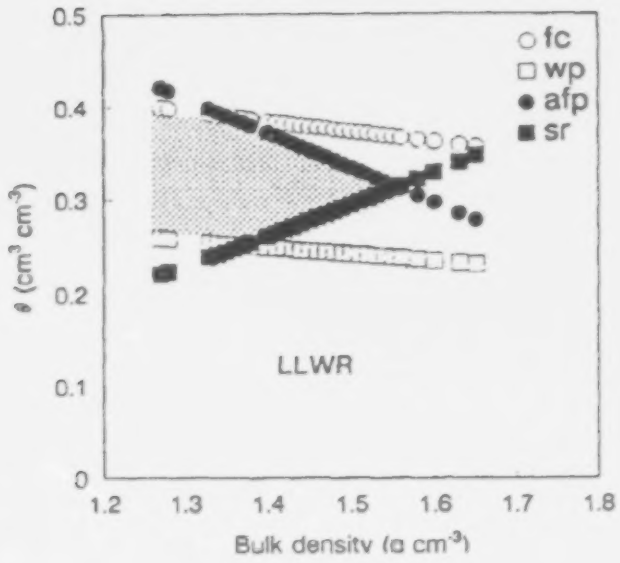

Figure 4. 2. Water content variation with bulk density at critical levels of field capacity (fc=1.5 MPa), at wilting point (wp=-1.5 MPa), at air-filled porosity (afp=10%), and at soil resistance (sr=2MPa)

The bulk density-dependent restrictions to plant growth shown in Figure 4.2 are specific to the silt loam soil and methods of measuring bulk density outlined by da Silva et al. (1994). However, the concept of NLWR and its interaction with bulk density can be generalized to all soils. A decrease in bulk density leads to a narrower water content range in which plant growth is unrestricted. If water content is above or below the NLWR, plant growth will suffer, due to high mechanical resistance, low available water supply, or lack of aeration. The more drastic the increase in bulk density, the greater the risk of lowered plant productivity.

Two of the sites (Ranfurly and Hayter 1) did not show significant differences in bulk density between wellsite lease and surrounding soil. We conclude that soil structure has been reformed on these sites, or that the structure of the B horizon was similar to that of

the removed A horizon. It's worth noting that the soils on these sites are coarse-textured; the mean particle diameter in both cases exceeds 40 μm.

In fact, we have found that particle size, or more precisely, particle size distribution is a fundamental property directly related to bulk density. Fine-textured soils, those with mean particle sizes < 15μm, are associated with large differences in bulk density between lease and control. Reclamation officers, consulted for purposes of wellsite certification in 1981 to 1983, recognized that clay content had increased on wellsites after topsoil removal. We confirmed this finding with our field examination and provide quantitative support with our lab data on mean particle size changes. Mean particle size is an excellent measure of changes due to wellsite development and reclamation. It can be calculated from laboratory hydrometer data on particle size, or it can be estimated precisely from texture (clay, silt, and sand) determinations (Shrazi and Boersma 1984). If quantitative comparisons are needed, as they were in this study, it is important to make sufficient measurements of geometric mean particle size to procure precise estimates of the average. Without good estimates of the average, qualitative comparisons, such as hand-textured estimates of clay, silt and sand, are the equal of laboratory measurements.

Organic matter and carbonate differences between lease and control soils are nearly as marked as differences in mean particle size, but unfortunately, our measurements of organic matter was not precise, nor accurate. The reason was that high carbonate levels contributed to variable measures of total carbon (organic carbon + carbonate), and imprecise estimates of organic matter. In retrospect, we should have measured organic matter by wet oxidation (Walkley and Black method), thereby not confounding organic carbon with inorganic carbon. On the other hand, carbonate measurements done independently of total carbon are relatively precise and consistent. Lease sites had significantly higher carbonate levels than control soils, as might be expected if subsoils are exposed. The relatively high levels of carbonate in all samples are a reflection of the underlying geology of central Alberta (Pawluk and Bayrock 1965) and the exposure of subsoils normally enriched with calcium carbonate. Semi-quantitative carbonate measurements using the degree of effervescence as the indicator of concentration could

be a simple method for estimating the admixture of subsoil with topsoil in central and southern Alberta. As more subsoil is mixed with topsoil, purposefully or inadvertently, carbonate levels and the degree of effervescence would rise accordingly. Calibration of the semi-quantitative scale could include observations of effervescence when tested on known carbonate concentrations and replicated measurements of unmixed subsoil and topsoil.

The final question we address with the results of this study is the relationship between soil structure properties, soil management requirements, and plant productivity. We've discussed how bulk density and plant productivity are interrelated through the non-limiting water range. We contend that there is sufficient evidence of increases in bulk density to suspect that plant productivity could be severely hindered by either excessive mechanical resistance to root growth or a decrease in available water supply. We made a few measurements of grain, oilseed, and forage production in 2002 that indicate lower production on lease sites where bulk density is highest. However, the spring and summer of 2002 was extremely dry and that cropping season followed several previous dry years. Hence, all crops suffered from lack of moisture, including the control soils in our experiments. Several years of crop growth data are needed to support or disprove the hypothesis that soils with increased bulk density will cause measurable decreases in plant productivity.

We developed an E-tiller capable of continuous measurement of tillage power requirements (expressed as pounds force). At a four-inch depth, corresponding approximately to surface soil and the depth of the bulk density measurements, the power requirements on- and off-lease were not different. The E-tiller could not detect the effect of bulk density changes in the surface four inches. Apparently, the soil management requirements, as measured by draft force at a four-inch depth, do not change significantly with the changes that we measured in bulk density.

On the other hand, the forces measured by the E-tiller at an eight-inch depth are significantly higher on-lease than in the surrounding soil. We did not measure the

physical properties of the subsoils by any other means, but draft force data would suggest significant compaction on at least four wellsite leases that we monitored at that depth. In conclusion, the E-tiller may not be sufficiently sensitive to measure differences in surface soil structure but there are unexplored differences in subsoil properties that might contribute to lower crop yields and increased power requirements during cultivation.

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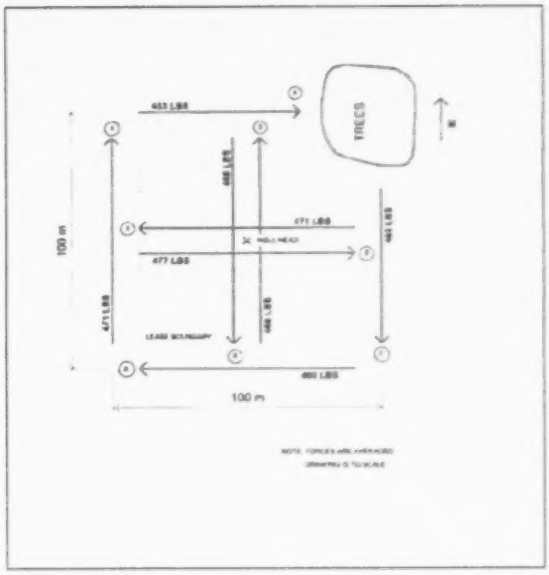
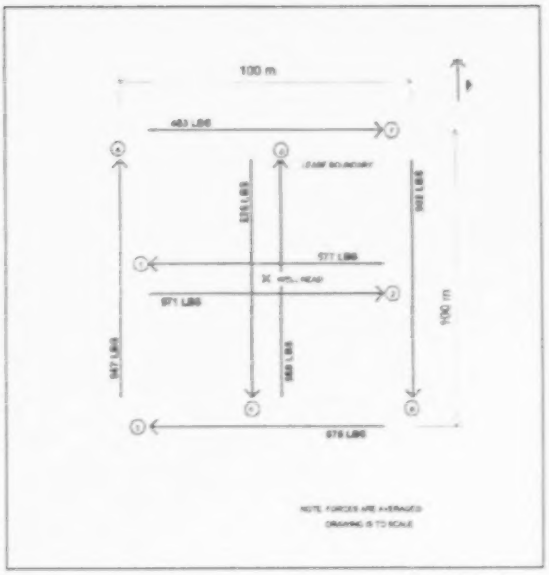
6. APPENDIX

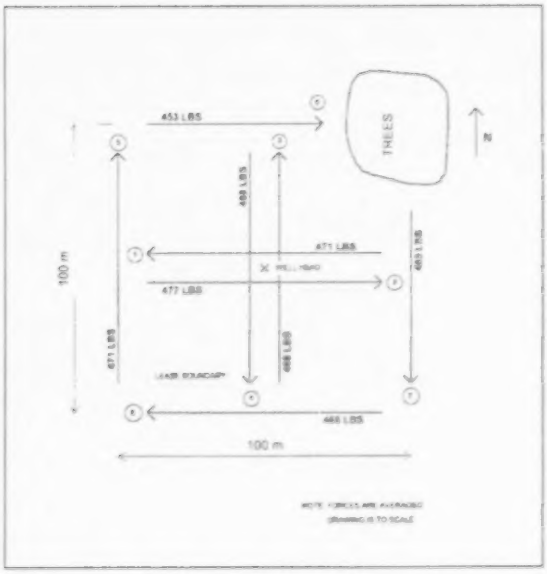
Hayter 1



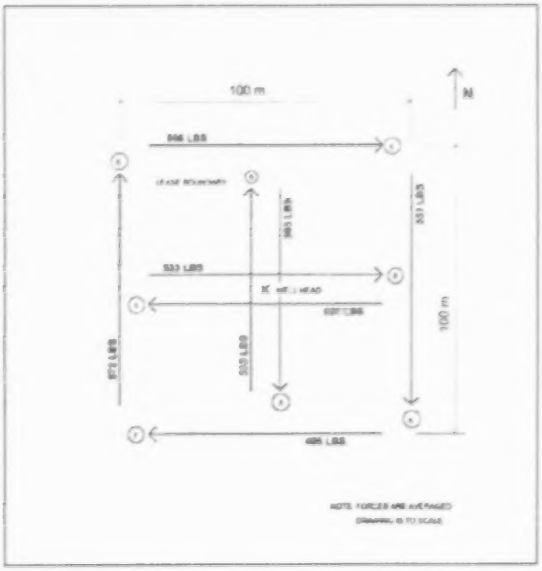
Rimbey

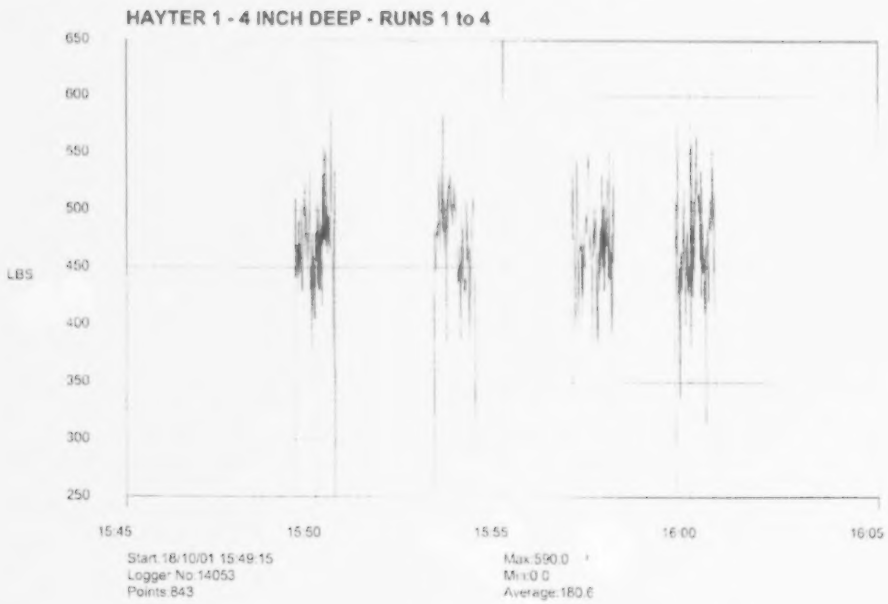


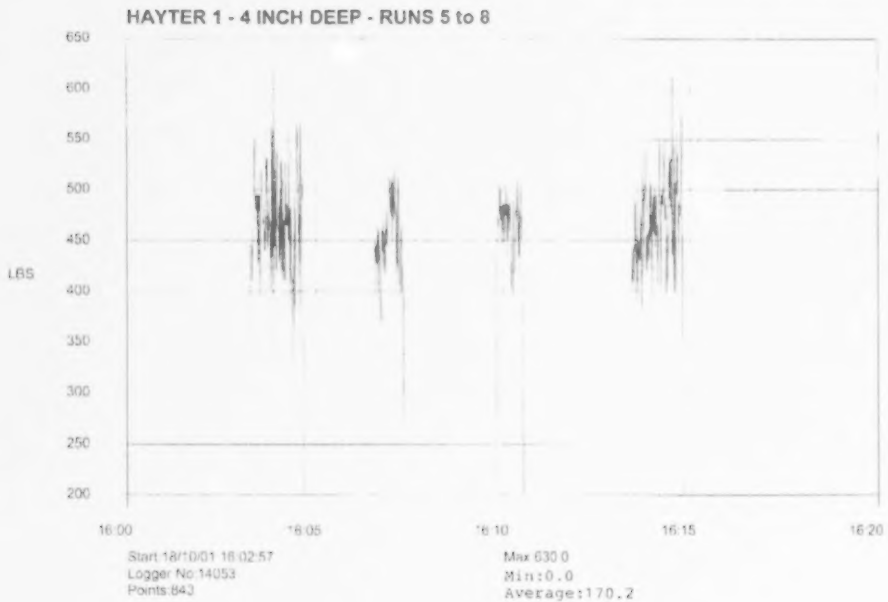
Hayter 2



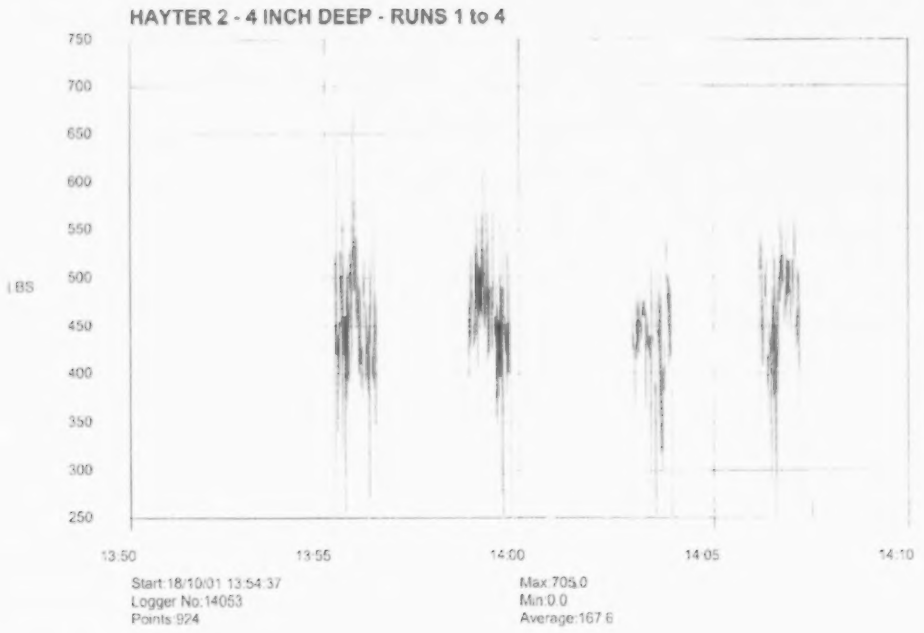
Olds

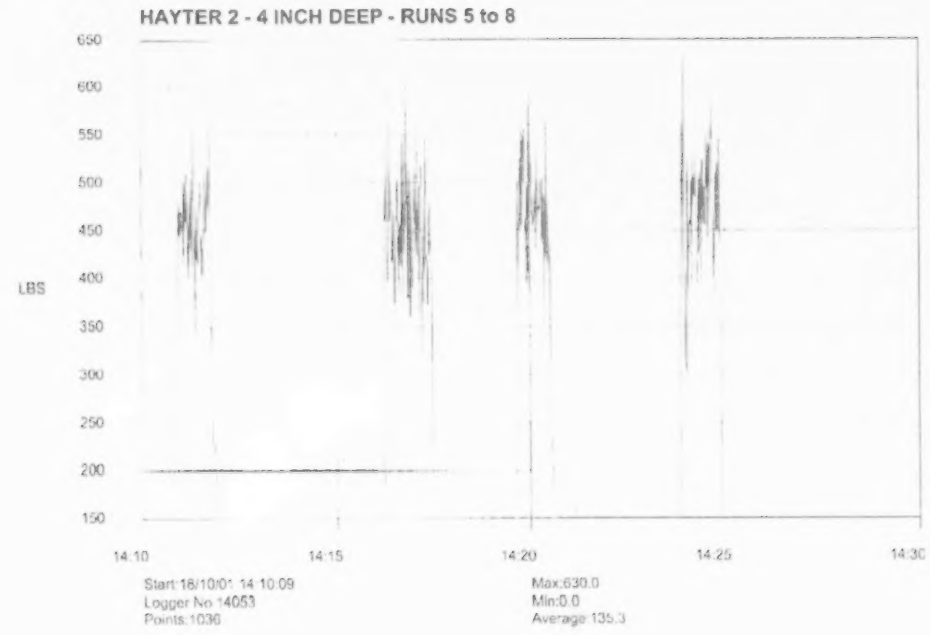




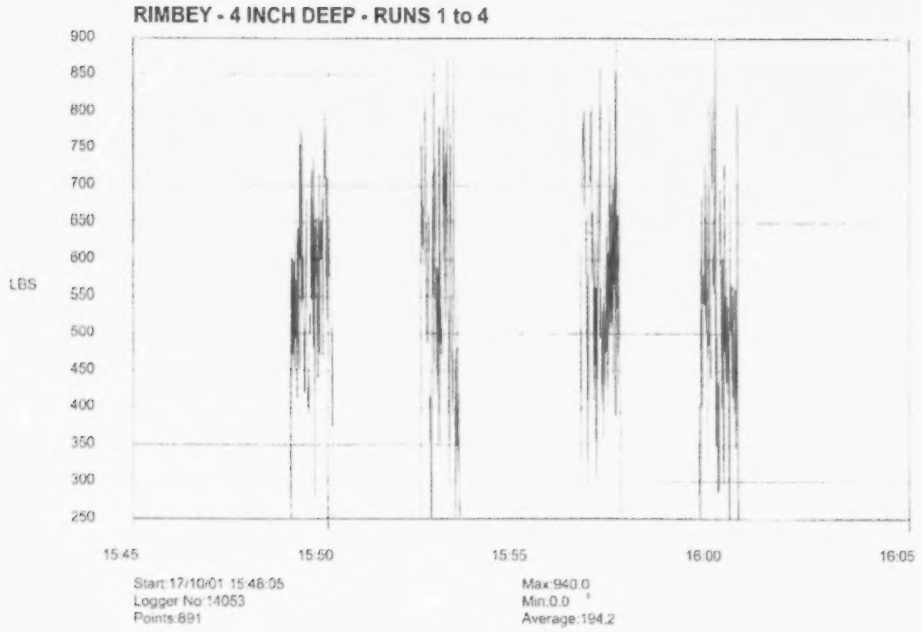


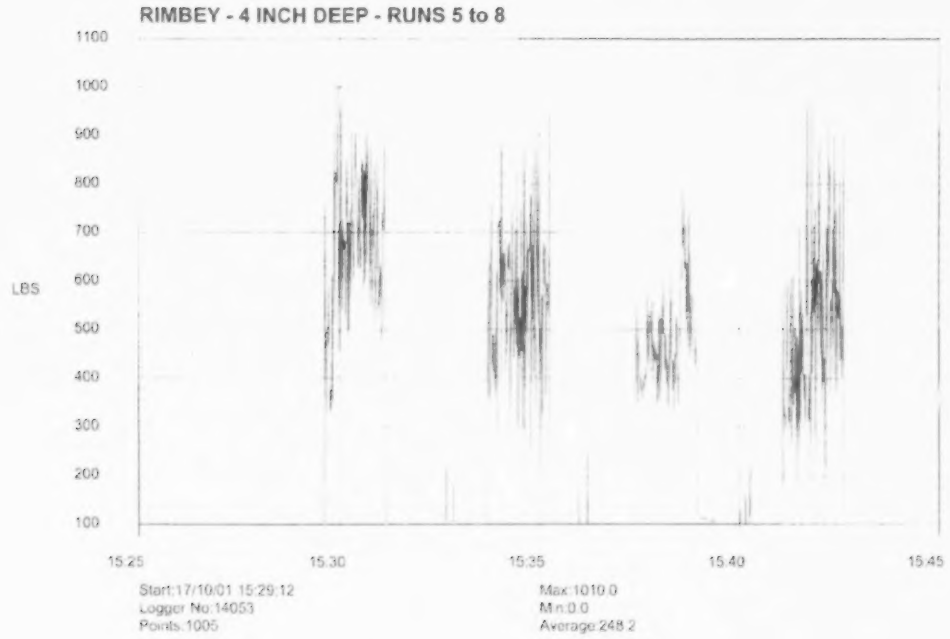
Actual record of draft forces (lbs) by site and pass (1-4 are on lease; 5-8 are off-lease)



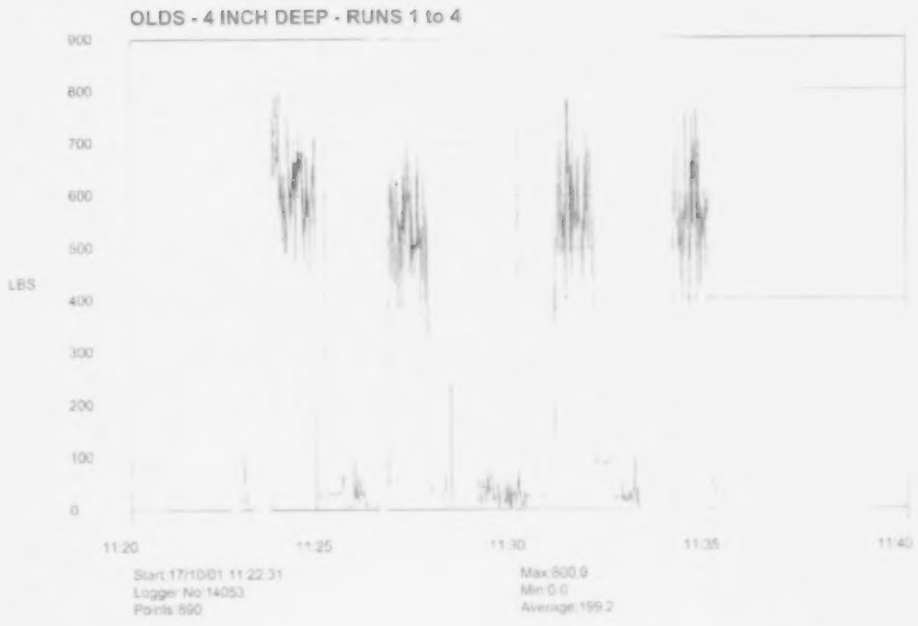


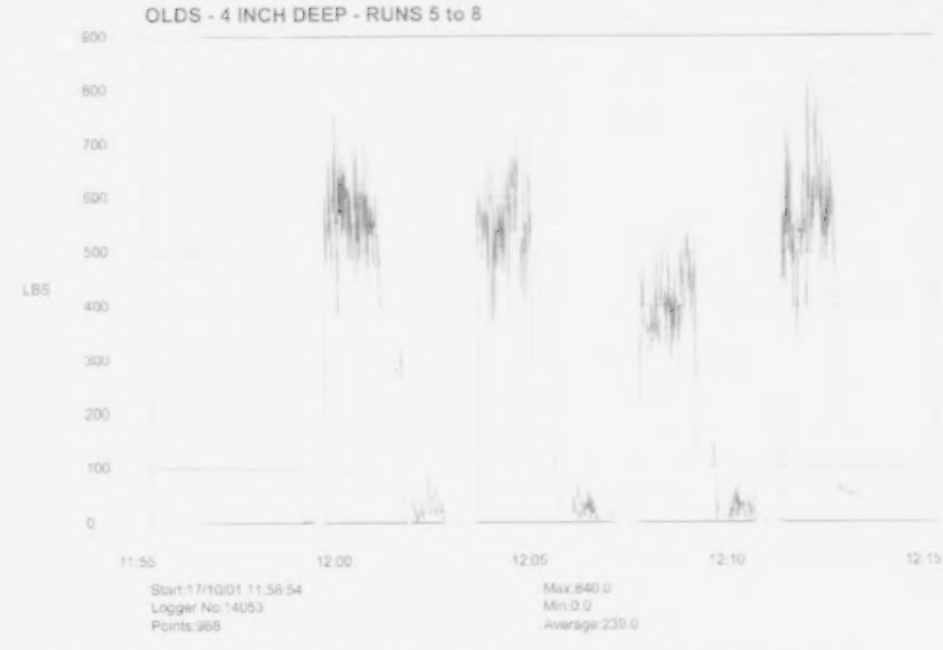
Actual record of draft forces (lbs) by site and pass (1-4 are on lease; 5-8 are off-lease) (Cont'd.)





Actual record of draft forces (lbs) by site and pass (1-4 are on lease; 5-8 are off-lease) (Cont'd.)





Actual record of draft forces (lbs) by site and pass (1-4 are on lease; 5-8 are off-lease) (Cont'd.)